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RESEARCH STUDY OF RADAR RELIABILITY AND ITS IMPACT ON LIFE-CYCLE COSTS FOR THE APQ-113, -114, -120 AND -144 RADARS

Reliability and Quality Assurance Staff
General Electric Company
Aerospace Electronic Systems Department
Utica, New York 13503

TECHNICAL REPORT ASD-TR-73-22

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Deputy for Engineering
Aeronautical Systems Division
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio 45433

NOTICE

RESEARCH STUDY OF RADAR RELIABILITY AND ITS IMPACT ON LIFE-CYCLE COSTS FOR THE APQ-113, -114, -120 AND -144 RADARS

Reliability and Quality Assurance Staff
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Aerospace Electronic Systems Department
Utica, New York 13503

FOREWORD

This report was prepared by the General Electric Aerospace Electronic Systems Department, Utica, N.Y. under USAF Contract F33615-72-C-1354 and Project 327F.

This is a retrospect study of the APQ-113, -114, -144 and APQ-120 Radar Reliability. This report, dated April 1973, covers the study period from September 1971 to June 1972 and is the final report under the contract. The Study Program was directed by General Electric AESD Manager of Reliability and Quality Assurance, S.G. Miller, and the Manager of R&QA Materials and Components, R.T. Simpson. The principal contributors to this Study Program report were A.M. Agnone, E.J. Benman, R.P. Collins, R.C. Kroeger, G.W. McKenzie, S.P. Mercurio, T.H. Poyer, D.I. Schmidek and L. Sperling.

Recognition is given to the many Air Force personnel at Griffiss, Hill, Nellis, Warner-Robins, and Wright-Patterson Air Force Base, who contributed to the report through providing essential data and consultation, as well as personnel at McDonnell-Douglas in St. Louis, Missouri, and General Dynamics in Fort Worth, Texas.

Technical surveillance of the contract was exercised by Mr. Griffith W. Lindsay and Mr. Tung-Sheng Liu (ASD/ENYS), Directorate of Systems Engineering, Deputy for Engineering, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio.

This technical report has been reviewed and is approved.

William A. Lusby, Jr., Colonel, USAF
Director, Systems Engineering
Aeronautical Systems Division

ABSTRACT

The purpose of this study was to provide insight into Reliability Worth through quantifying the relative values of reliability activities and their impact on life cycle costs. This study is based on APQ-120 and APQ-113, -114, and -144 Radar reliability data, spanning only a specific time period of their development, and therefore the findings presented are limited to the equipment configurations included in the data base and the specific time period studied. In-service reported reliability performance data was analyzed for both radar families, the objective being to correlate differences in reliability performance with the equipment reliability requirements and programs structured. Reliability program elements instrumental to the development effort are analyzed to determine relative worth. Considerable emphasis is placed on reliability evaluation testing, parts screening, and equipment burn-in which are identified as major contributors towards achieving demanding equipment reliability performance.

This report finds that optimum maturity of radars, prior to deployment, requires extensive and well-directed development effort as an investment measured in cost and time.

The report also recognizes and supports the importance of uncompromising contractual incorporation of MIL-STD-781 at applicable airborne stress levels as the principal driving force in establishing and executing effective reliability development effort.

Based on the experience of the equipments studied, it is concluded that timely, sufficient and properly directed reliability program investment can produce significant cost savings leverage when compared against the projected equipment life cycle maintenance costs for unreliable equipment.

Recommendations are provided, based on conclusions derived from study findings, relative to reliability contracting practices, prerelease disciplines and testing programs, specifically applicable to high performance aircraft avionics equipments.

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SECTION I

REPORT INTRODUCTION

A. MANAGEMENT OVERVIEW

This report is a Reliability Study of the APQ-113, -114, -120, and -144 Radars. Comparisons of their reliability requirements, programs, and results provide the basis for the analysis developed of the effectiveness and value of the reliability disciplines applied.

The radars studied were conceived and constructed during the 1960s for use on high performance aircraft and are similar in functional capability, parts count complexity, and acquisition cost.

This report concludes from comparisons made between the high performance aircraft radar programs studied that the differences in results attained, both in reliability test and field reliability performance, can be partially attributed to differences in contract reliability requirements and the resultant contractor's reliability program. This is particularly applicable for the MTBF and reliability test requirements.

It is reasoned that demanding, achievable, and measurable contract reliability requirements contribute substantially to optimized reliability achievement by dictating design disciplines effective in controlling equipment parts count complexity, material quality level selected, and parts application stress levels.

The selection and specification of reliability test requirements is also considered particularly important, in that dynamically structured reliability growth testing programs are necessary in providing the means to achieve the equipment's inherent reliability capability. This is shown to be the case for new radar designs where the initial equipment test performance was only approximately 10 percent of the predicted or inherent MTBF capability. The analysis provided in this report attributes this constrained initial reliability performance to subtle design, quality, and material problems, which are found to occur in approximately equal proportion (1/3, 1/3, 1/3). While these defects can and must be minimized by the emphasis given in pre-release design efforts, equipment testing must be performed to identify residual defects.

The report attributes the disparity existing between measured test and field MTBF to factors such as time base, failure definition and accounting, and stress level differences. Reconciling these differences and apportioning the effects of these factors is important, primarily so that the effectiveness of reliability test programs can be evaluated and improved.

The test measurement is found to be more precise than the field, in the areas of the readily identifiable factors such as time base and failure definition and accounting due to the advantage of the test being conducted under standardized controlled conditions.

However, the test results may not be a useful indicator of field reliability performance, regardless of measurement precision, if the stresses of the test program do not encompass those to be encountered in the field environment. For this reason, the report recommends using only MIL-STD-781, at appropriate test levels, and permitting no deviations unless the field application is more severe. In conjunction with this recommendation, considerable report emphasis is placed on timely reliability testing to take advantage of the opportunity to identify and correct problems early in the equipment development cycle, thereby minimizing or precluding deployment of unreliable equipment. Field data presented lends support to this recommendation in that it indicates that the reliability of the equipment studied did not grow, once field deployed.

The report describes a General Electric Company developed methodology entitled Reliability Planning and Management (RPM), useful in determining the test hours required during development to achieve a given test MTBF based on initial equipment capability and the rate of MTBF growth alpha (α). Based on RPM's fundamental premise that reliability growth in this context is real and projectable, a provision is included for monitoring of equipment reliability growth performance versus plan during the program testing phase.

In addition, RPM enables evaluation of tradeoffs by both contractor and buyer in program planning encompassing the acceptability of the initial design, design margin, number of equipments to be placed on test, facilities, test time, calendar time, and program cost, beyond the minimum requirements of MIL-STD-781.

An analytical derivation of the factors influencing and limiting the rate of reliability growth alpha (α) is provided. This analysis shows that alpha is influenced primarily by the systematic and permanent removal of failure mechanisms through identifying defects and taking corrective action, the rate and efficiency of failure removal, and the distribution of system failure mechanisms. Maximum reliability growth rate is shown to occur when a reliability test program is structured to detect and remove every systematic failure source (alpha = 0.6).

The report provides a mathematical model relating the cost factor variables associated with reliability growth testing with selected factors impacting equipment life cycle maintenance costs. The model developed has been generalized in a computer program capable of evaluating optimum reliability test investment, dimensioning MTBF goals, estimating test schedules and testing the sensitivity of the chosen reliability factors for a variety of conditions. The approach presented provides the opportunity for making objective cost analysis tradeoff decisions regarding the effective amount of reliability growth test investment within the context and limits of stated simplifying assumptions.

The report concludes that the cost just to maintain unreliable equipment over its planned life cycle can far exceed the initial procurement costs associated with the reliability growth test program advocated herein. In an example provided utilizing data representative of the APQ-113 procurement history, the additional investment in reliability growth testing is shown to have a favorable cost savings leverage of approximately 50:1 (maintenance savings : reliability growth test investment).

The report dimensions the total reliability development program investment including all the prerequisite MIL-STD-785 elements necessary to produce these results as approximately 20 percent of an RDT&E Program based on the APQ-113 reliability program described. Other cost analyses provided show that the APQ-113 decisions to use hi-rel electronic parts, and to 100 percent precondition assemblies by temperature cycling, were also cost effective.

This report reinforces and amplifies the rapidly growing volume of evidence that reliability investment properly directed does produce significant cost saving dividends. Also, it emphasizes the merits of the Air Force reliability policy, thus encouraging its extended implementation.

B. SUMMARY OF REPORT SECTIONS

Section I provides a management overview of this report and contains summaries of key report findings, conclusions, and recommendations. Also included is essential background material covering the programs and products studied, as well as the data utilized and its sources.

Section II presents the development of the Reliability Planning and Management (RPM) methodology, an analytical derivation of reliability growth rate, and cost modeling dimensioning reliability program investments and assessing the effectiveness of reliability growth testing, and parts and product screening.

Section III describes the reliability program elements, disciplines, and results during the RDT&E and production contract phases for the radars studied.

Section IV discusses and compares the radar reliability test programs conducted and their results.

Section V describes the relationships between the specified radar environmental test requirements and conditions, as compared to the test stress levels applied and the field environments encountered.

Section VI analyzes Air Force reported radar field performance based on 66-1 data covering the time period of December 1970 through November 1971. Some additional insight is provided based on reported experiences of the airframe contractors involved.

Section VII contains the study contractor's recommendations for improvements to reliability contract documentation and practices specifically applicable to complex high performance aircraft avionics.

C. SUMMARY OF REPORT FINDINGS

NOTE: The findings presented herein relate to high performance aircraft avionics, are based on the data available, and are limited to the equipment configurations included in the data base and their development status at that time.

1. RELIABILITY DISCIPLINES AND VALUES

- Reliability growth can be real and projectable under specified conditions between well-defined practical and theoretical limits.

- The analytical derivation of reliability growth (α) has shown that the underlying mechanisms which influence α are:

  - Distribution of failure mechanisms

  - Detection of failure mechanisms

  - Rate of failure removal

- With a uniform distribution of failure mechanisms, a maximum reliability growth rate (α) of 0.6 can be achieved.

- Investment in reliability growth testing to achieve the APQ-113 reliability objectives is shown herein to provide life cycle maintenance savings as high as 50:1 (savings to test investment) when compared to projected maintenance cost if the test investment had not been made.

- APQ-113 experience demonstrates that reliability predictions using credible part failure rates are achievable in equipment performance when reliability growth programs are planned and executed.

- Design inheritance is shown to be a factor in off-the-board reliability performance.

- APQ-113 Hi-Rel (screened) parts improved part failure rate by a factor of 10:1 and observed field reliability by no less than 4.

- APQ-113 Parts Screening and Product Screening to prescribed conditions were cost- and reliability-effective. Parts Screening cost effectiveness is shown herein to be 2:1 (savings : cost). Product Screening cost effectiveness is shown herein to be 4:1 (savings : cost).

- Field maintenance cost per radar for the APQ-120 equipment configurations studied is reported to be approximately three times higher than the APQ-113, -114, -144. (AFLC Report K051 (10-71))

2. RELIABILITY PROGRAM ANALYSIS

- APQ-113 environmental product screening was effective in precipitating an additional amount of failures equal to all factory ambient tests combined, reducing platform failures by a factor of five.

- The APQ-120 and APQ-113 had significantly different factory test flow plans. Particularly, equipment environmental test screens were applied to the APQ-113.

- APQ-113 workmanship-induced failures were practically all removed by product environmental screening before the equipment left the factory.

3. PRODUCT ASSURANCE TEST PROGRAMS AND ENVIRONMENTAL CONDITIONS ANALYSIS

- Initial APQ-113 $\bar{R}$ demonstration MTBF was 10% of predicted, constrained by problems which were one-third design, one-third workmanship, and one-third parts. Reliability growth testing was needed to progress from this 10% to compliant MTBF.

- Differences in MTBF between field and factory are attributed in part to differences in environmental profiles. APQ-113/114/144 are exposed in flight to cooling air and vibration conditions markedly different from factory environmental qualification and RQT.

- Twice as many failures were observed at low temperature as high temperature during RQT.

4. FIELD PERFORMANCE ANALYSIS

- F-111 radars (APQ-113/114) exhibited a 2.5 to 4.0 times higher field $\bar{R}$ rate than the F-4E (APQ-120) as reported June-Nov. 1971 (RCS 6 LOG K261).

- The F-111 aircraft avionics equipments exhibit an average $\bar{R}$ rate equal to 20% of factory demonstrated MTBF. Similar patterns are observed for avionics equipments aboard other high performance aircraft (F-4D, F-4E, A-7E). The APQ-120 R rate is 200% of its demonstrated MTBF.

- Differences between field $\bar{R}$ rate and factory demonstrated MTBF are explained in retrospect for the equipments studied through factors accounting for dissimilarity of environmental profiles between RQT and flight, flight hours versus ON-hours, and diagnostic capabilities.

- Field data shows no reliability growth on APQ-113/114 and APQ-120 during the five years of field deployment.

- Reliability predictions reflecting failure rates consistent with the quality of material are a good indicator of product performance.

- Electrical, Electronic and Electromechanical (EEE) part failure rates (Replacement Rates) at platform and field were lower by approximately one order of magnitude on APQ-113/114 than on APQ-120, which is attributed to differences in program parts screening.

- The 15:1 estimated lower cost of failures at platform, for the APQ-113/114 versus the APQ-120, is attributed to the factory environmental preconditioning of the APQ-113/114.

D. SUMMARY OF REPORT CONCLUSIONS

NOTE: The conclusions as presented herein relate to high performance aircraft avionics as they are based on the findings for the equipments studied, but have been generalized in the belief that broader application is merited.

1. PRERELEASE RELIABILITY PROGRAM

- Challenging but achievable reliability specifications should be derived based on required equipment functional capability and also considering optimization of RDT&E reliability program investment with projected life cycle maintenance costs.
- Demanding reliability requirements are essential to optimize equipment reliability capability, constrain design complexity, necessitate selection of high quality parts, and discipline parts application.
- Meaningful and demanding equipment reliability performance can be achieved and demonstrated as part of RDT&E programs, if contractually specified as requirements, and uncompromisingly enforced.
- Analytical predictions of demanding reliability performance are achieveable, using credible part failure rates, and dynamically structured reliability growth testing programs.

2. PRODUCTION RELIABILITY PROGRAM

- Equipment Design Maturity/Stability - New product designs should not be released for volume manufacture until reliability qualification testing has certified that the equipment meets its specified reliability requirement.
- Production Test Program Structure - The manufacturing test program structure establishes the effectiveness of product screening and the quality level of the product delivered; therefore, the minimum production program test structure for complex avionics products utilized in high performance aircraft environments should be contractually specified and approved.
- Problem Identification and Solution
    - Reliability programs must be structured to provide for the timely identification and elimination of all design, material, and workmanship pattern problems in order to achieve maximum rate of equipment reliability growth.
    - Measurement of equipment reliability using unanalyzed failed part data will be biased unrealistically low based on APQ-113 factory experience revealing that typically 30 percent of factory test reported part failures, when analyzed, cannot be verified as failed parts.

- Part failure analysis needs to be maintained throughout a production manufacturing program because of subtle design and process changes as well as lot-to-lot quality variation problems, continuously introduced by part suppliers.

- Existing electrical part screens need to be improved as typically 35 percent of the equipment test level verified failures of screened material had assignable causes attributable to supplier responsibility.

3. RELIABILITY TRADEOFF DECISIONS

- Equipment complexity needs to be contractually limited, consistent with functional capability, to preclude parts count escalation and its attendant negative impact on reliability performance and life cycle maintenance costs.

- One hundred percent parts screening is necessary to meet demanding reliability requirements and provide effective control of the quality of purchased parts.

- Complex electronic products having demanding reliability requirements and high performance aircraft applications must be 100 percent screened, during manufacture, in the most severe end use environment but no less than MIL-STD-781 requirements.

- Subcontracted items must be subjected to the same reliability requirements and disciplines applied to the prime equipment and environmentally qualified as end items.

4. QUALIFICATION TEST

- Environmental and Reliability Qualification test requirements should be considered as an integrated product qualification test requirement.

- Equipment cannot be considered qualified and should not be committed to volume production until both environmental and reliability qualification tests are successfully completed.

- Time must be structured in RDT&E programs for Reliability Growth Testing.

- Reliability Acceptance Testing of the production equipment population is needed for assuring the qualified reliability level is sustained throughout production.

- Reliability Qualification test acceptance plan criteria need to be simplified. The variety of confidence limits, measured, specified and demonstrated values create unnecessary confusion.

5. ENVIRONMENTAL

- The scope of reliability test stresses should approach worst case design limits with performance measurements made at high, low and room temperature.

- The minimum reliability test environmental levels should be established based on the most severe equipment use conditions - but in no event below MIL-STD-781 requirements.

- To minimize differences in factory to field environmental profiles, random spectrum vibration should be introduced into environmental qualification testing.

6. FIELD AND PLATFORM

- Avionics equipment field reliability performance will be improved by factors of 4 to 10 if prerelease and production practices of reliability growth testing and parts and product screening are implemented.

- Significant equipment reliability growth is practical only via factory reliability test programs because, once equipments are field deployed, problem identification and correction become increasingly difficult, more costly and less timely.

- Reliability test measured MTBF and field reported R rate (66-1 MTBF) differences can be explained through retrospect data analysis for the specific equipment by establishing common baselines of environmental conditions, time measurements and failure verification.

- The problem of field failure verification could be reduced through improved design maintainability, increased BITE capability and environmental troubleshooting facilities at the Base Maintenance and Depot shop levels.

- Material quality consistent with TX, ER or MIL-M-38510 will maximize performance and minimize costs. Substitution of lower grade material in field repairs should be prohibited.

E. PROCUREMENT CONSIDERATIONS SUMMARY

1. RELIABILITY CONTRACTING POLICY

- Insure that MIL-STD-785 is imposed on Avionics contracts.

- Elevate the stature of reliability requirements in the overall program context so that tradeoffs will at a minimum be on a par with other performance requirements.

- Instill the fear of failure to meet contractual reliability requirements on both sides -- the contractor and the government program manager.

2. RELIABILITY CONTRACTING PRACTICES

- Realistically establish and dimension the reliability requirements.
- Provide for reliability growth programs.
- Objectively evaluate the contractor's ability to comply.

3. DEVELOPMENT CONTRACT PENALTIES

- Test and corrective action continuance until the reliability requirements are achieved.
- Production authorization withheld until the reliability requirements are achieved.
- Correction of deficiencies in delivered hardware.
- Extended contractor in-service warranties.

4. RELIABILITY CONTRACTING DOCUMENTATION

- Modify MIL-STD-785 to incorporate R growth concepts during development.
- Establish a training handbook for planning and control of reliability growth.

5. PRE-PROCUREMENT

- Establish reliability growth planning and measurement dialogue between procurement and contractor management, initially utilizing the RPM parameters of this study. Encourage modification and improvement in the use of these measurements from experience of on-going programs.
- Incorporate current Reliability Planning and Management (RPM) methodology into pre-procurement by:
  - Advanced planning of reliability requirements in concept stage
  - Requiring evaluation and pricing of reliability tradeoffs
  - Trading off reliability with other functional requirements
  - Structuring reliability growth
  - Requiring assessment of the degree of design inheritance
  - Updating and disseminating failure rates at relevant stress levels

- Building upon RPM parameters of this study
- Require contractor and contracting officer to consider overall program costs including equipment and field support as a basis for contract award.

F. PROGRAMS AND PRODUCTS

1. INTRODUCTION

This part of the report describes the APQ-120 and APQ-113 series of radar equipments studied, their design inheritance, and functional capabilites. Comparisons are drawn as to equipment complexity, acquisition and logistics support cost, and reliability requirements. The primary objective is to establish the base line for the material content of the balance of this reliability study.

2. DESIGN INHERITANCE

Both radars were conceived and constructed during the 1960's for use on high performance aircraft. The APQ-120 was a repackaged solid state design which evolved from its tube type predecessors, the APQ-100 and APQ-109, with much of its initial design being performed on the R&D of the APQ-117. The APQ-120 program through 1971 has spanned seven years, producing an ivalent of 1050 radars. The APQ-113, on the other hand, was a new design contracted as part of the initial F-111 procurement. Coupled with the APQ-114 and -144 contracts, a total of 560 equivalent radars were designed and delivered over a nine-year period (Figure 1). Significant differences are observed in RDT&E program calendar time and in production quantities and rates.

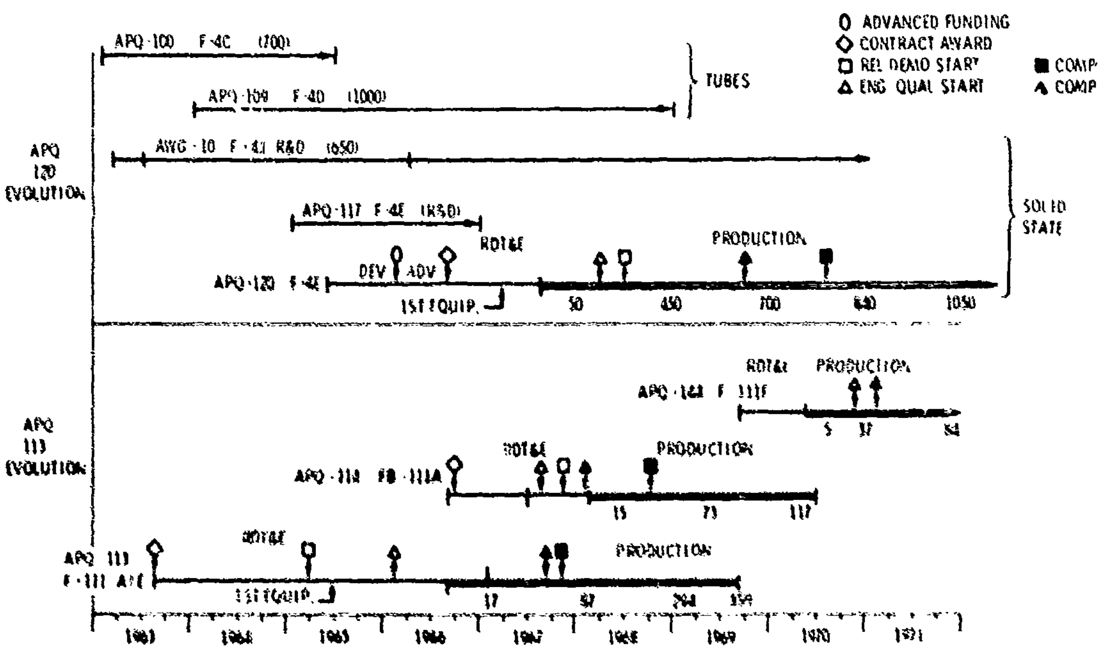


Figure 1. Design Inheritance, APQ-120 and APQ-113

3. COST COMPARISONS

The radar contractor RDT&E programs are nearly identical when considering total cost aspects (Table I). Additional cost similarities are found in the AFLC K051 report for Air Force radar spares acquisition, yet the monthly logistics support cost per APQ-120 equipment was $746, compared to $299 for the APQ-113, a 2.5 to 1 cost differential.

TABLE I. COST COMPARISONS

	F-4E APQ-120	F-111A APQ-113	F-111E APQ-113	FB-111A APQ-114
RDT&E				
CONTRACT VALUE	$24.2 M	$17.7 M		
EQUIPMENT QUANTITY	9	24		
DESIGN & DEVELOPMENT COST		$7 M		
COST PER RADAR				
* AIR FORCE SPARES ACQUISITION	$242.7 K	$276.8 K	$217.8 K	$235.3 K
			243.3K AVG	
*LOGISTICS SUPPORT				
AIRCRAFT QUANTITY	564	118	91	66
MONTHLY COST/RADAR	$746	$299	$266	$166
		2.5:1	2.8:1	4.5:1

*SOURCE: AFLC REPORT K051 (10-71)
DATA FROM 7-71 THRU 9-71

4 RELIABILITY PROGRAM COMPARISON SUMMARY

The radar equipments are of similar design vintage, functional capability, parts count complexity, acquisition cost, and application, yet had 15:1 different contractually specified MTBF reliability requirements which were to be demonstrated in Reliability Qualification Test. The contracted reliability requirements at 90% lower confidence level for the APQ-120 was 9 hours Mean Time Between Failures (MTBF) compared to a requirement of 134 hours for the APQ-113.

The APQ-120 demonstrated 4.3 hours MTBF or 50% of its requirement while the APQ-113 exceeded its requirement by 12% with a demonstrated 152-hour MTBF. The test measured reliability MTBF ratio of 35:1 between the APQ-113 and APQ-120 is attributed to the difference in specified reliability requirements, the resulting reliability programs structured, and the uncompromised customer enforcement of the APQ-113 requirement.

APQ-113		APQ-120
≈10,700	Equipment Complexity - Parts Count	13,500
89%	High Reliability Parts Content	24%
134 hr	MTBF Required (at 90% LCL)	9 hr
178 hr	MTBF Predicted	45 hr (est)
MIL-R-26667A Level 3	Reliability Test Specification	MIL-STD-781A Level E
Not timely	Reliability Test Timing	Late
≈10,000 hr	Reliability Evaluation Test Hours	0
152 hr	Reliability Demonstrated (at 90% LCL)	4.3 hr
1413 hr	Relevant RQT Hours	96 hr
7000 hr	Reliability Acceptance Test Hours	0
100%	LRU Environmental Screening	0

The reliability requirements and programs for both radars are examined and discussed in further detail within the body of this report. The greater reliability challenge presented by the APQ-113 MTBF requirement is given credit for many of the differences observed in the design and manufacture of the radars studied. As an introduction to the study conducted, a brief description of the equipment is provided.

5. EQUIPMENT CAPABILITY AND DESCRIPTION

RADAR EQUIP.	COMPLEXITY ELECTRICAL PARTS	NO OF ELEC LRUS	FUNCTIONAL CAPABILITY																	
			AIR-TO-AIR						AIR-TO-GROUND											
AN/APQ			SEARCH	DETECTION	LCOSS DISPLAY	TRACKING	MISSILE ILLUM	AIM ON JAMMING	MAPPING	RANGING	STAB. TRKG. DISPLAY	N. ORIENTED DISPLAY	NAV FIXES	CRT DISPLAY	BITE	COMPUTATION	BEACON CAPABILITY	AERO PHOTOGRAPHY	ECM FEATURES	TV MODE
120	13,553	19	■	■	■	■	■	■	■	■				■	■	■	■		■	■
113	10,704	8	■	■		■			■	■	■		■	■	■	■		■	■	
114	11,160	8	■	■		■			■	■	■	■	■	■	■	■	■	■	■	
144	11,545	8	■	■		■			■	■	■	■	■	■	■	■	■	■	■	

■ CAPABILITY

Figure 2. Equipment Capability Comparison

Functionally, the APQ-120 is primarily Air-to-Air and the APQ-113 is Air-to-Ground (Figure 2).

a. APQ-113 Radar LRUs (Figures 3 and 4)

LRU 1 - The Antenna, utilizing a flexible diaphragm to provide pencil beam or ground mapping patterns, scans in azimuth either ±45 degrees about the longitudinal axis of the aircraft or ±10 degrees about a movable azimuth cursor. Automatic stabilization in pitch and roll is accomplished by signals from the bomb/nav equipment, and elevation positioning within 30 degrees of the horizontal is performed either manually or by a depression angle signal also provided by the bomb/nav equipment. Contained within the main antenna is an auxiliary Broad Beam Antenna for sidelobe cancellation.

LRU 2 - The Pedestal is attached to the most forward bulkhead of the aircraft and serves primarily as a mounting and roll-stabilized platform for the antenna assembly and for two antenna-receiver units of the terrain-following radar (TFR).

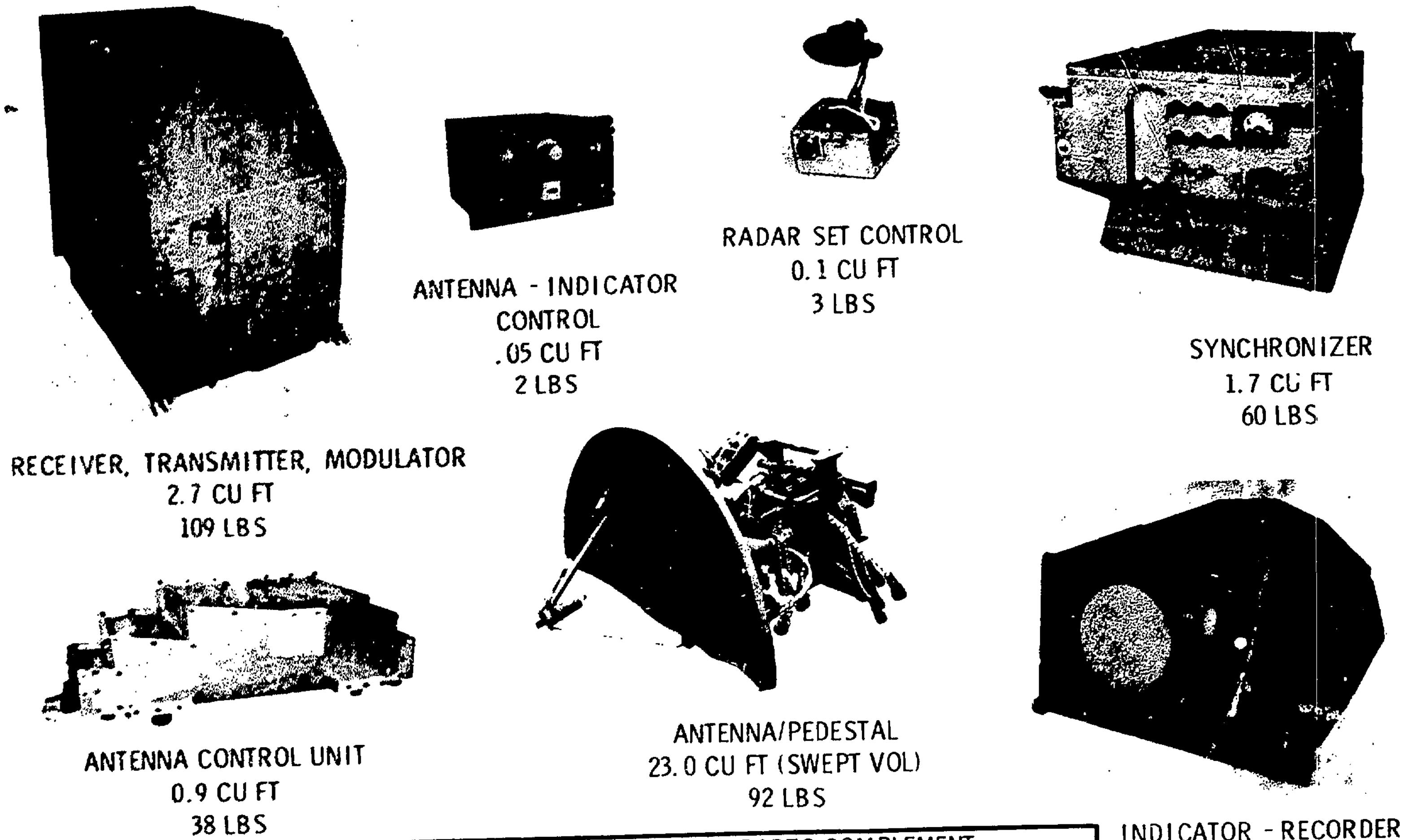
LRU 3 - The Antenna Control Unit (ACU) senses and compares antenna and roll platform position with the bomb/nav equipment command and pilot command inputs for movement about the four gimbals: azimuth, pitch, tilt, and roll. If a difference exists between sensed and input positioning commands, the ACU provides drive power for correction.

LRU 4 - The Receiver-Transmitter-Modulator (RTM or MRT) provides high voltage for the generation of high power RF energy pulses to be transmitted at random or set frequencies. The echo signal is then displayed on the radar scope within the aircraft. During random frequency operation, the magnetron output sweeps through the frequency band, which improves the stability of return signals and also provides a measure of immunity to various jamming frequencies. Sidelobe signals may be cancelled at the video level.

LRU 5 - The Electrical Synchronizer (Sync) provides timing for the attack radar, contains the radar's regulated DC power supplies, generates range marks for the radar scope display, provides automatic angle tracking of air targets, and supplies range and range rate information to the lead computing optical sight (LCOS) for gun and missile firing control. It also generates precision range and azimuth cursors; supplies the receiver with signals for automatic gain control, and during self-test monitors radar operation for in-flight or flight line malfunction detection and isolation.

LRU 6 - The Indicator Recorder (I/R) provides a radar scope display, tuning control, deflection and amplification circuits, and an integral camera. The display is a plan position indicator (PPI). Also contained within the unit is an integral camera which manually or automatically photographs the back of the CRT display.

LRU 7 - The Radar Set Control (RSC) provides power, mode, and function controls for signals to be sent to all units of the attack radar.



WEIGHT (LBS)	INPUT POWER (WATTS)	AN/APQ 144 - PARTS COMPLEMENT				
		INTEGRATED CIRCUITS	SEMI-CONDUCTORS	TUBES	PASSIVE	TOTAL
370	1550	1081	3040	19	7405	11545

Figure 3. APQ-113 Radar

LRU 8 - The Antenna/Indicator Control, during the Air Mode of operation, controls antenna tilt; changes antenna scanned sector from wide to narrow; provides rapid slewing of the range cursor; and positions azimuth and range cursors for navigation, bombing, and target tracking.

LRU 11 - The Electrical Equipment Rack supports the RTM and Synchronizer in the aircraft's forward equipment bay.

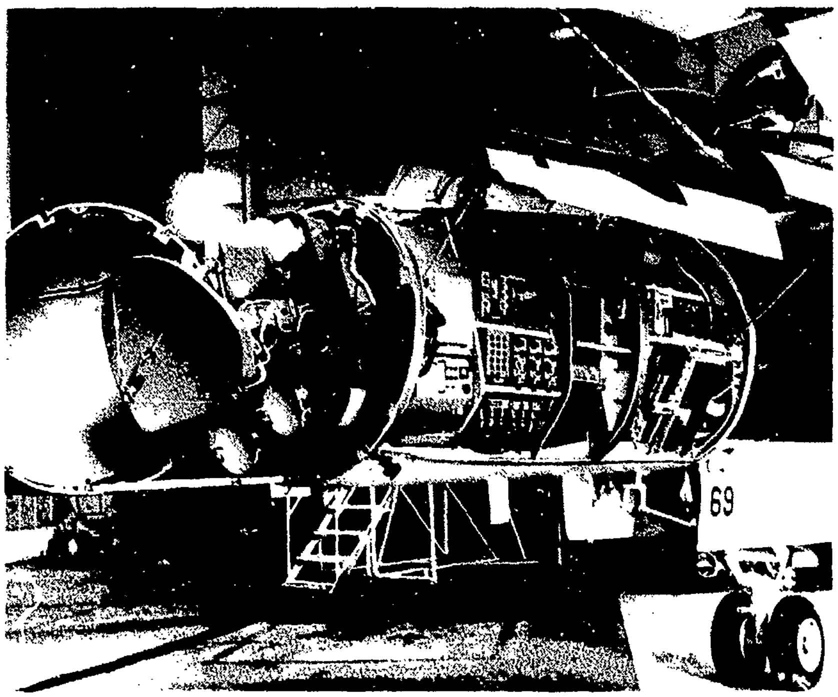


Figure 4. F-111, With Radar Exposed

b. APQ-120 Radar LRUs (Figures 5 and 6)

LRU 1 - Target Intercept Computer - Interceptor flight data and target information are fed to the intercept computer which determines the interceptor flight path and calculates the permissible launch zones for the missile. The computer, capable of solving an attack problem and transmitting the results to the display indicator, has as its outputs the interceptor steering commands, the launch zone signals, and the missile prelaunch commands.

LRU 2 - The Radio Frequency Amplifier produces and amplifies the frequency-modulated CW, RF energy required to illuminate a target for the missile guidance equipment.

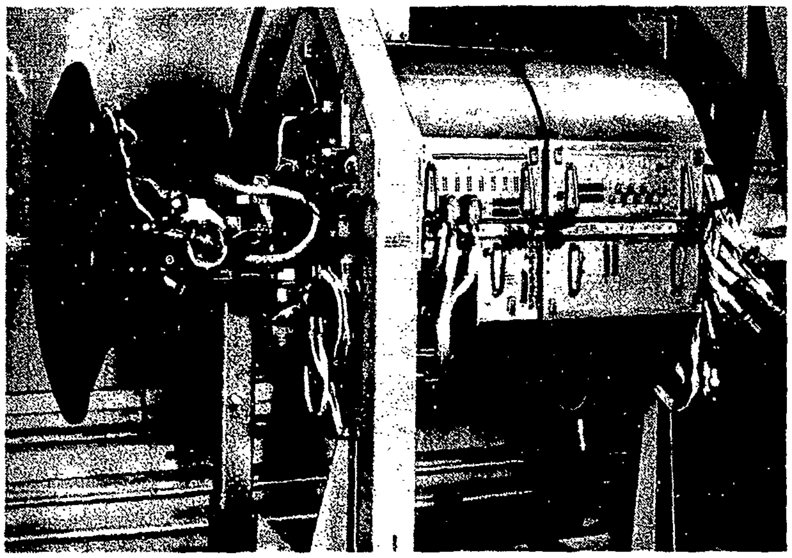


Figure 5. APQ-120, Port Side

LRU 3 - The Modulator-Oscillator contains the circuits required by the missile for prelaunch tuning. It provides both the ranging and amplitude modulated coding signals and performs the required modulation of the carrier. Also provided is automatic power leveling of the klystron power amplifier (KPA) drive signal.

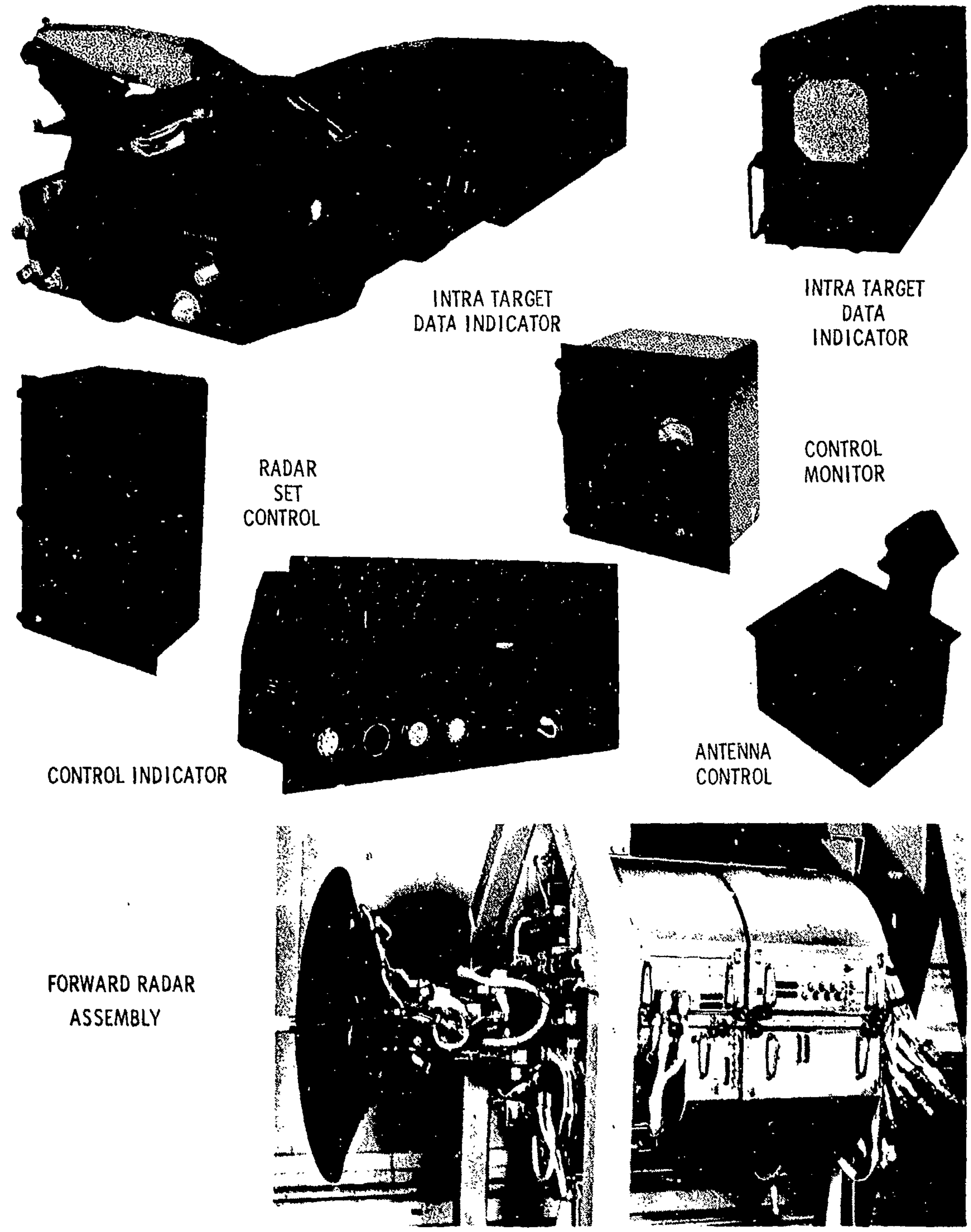
LRU 4 - The Stabilizer Assembly receives and uses aircraft pitch, roll, and drift information to stabilize antenna drift in air-to-ground mode or PPI sweep drift in map-PPI modes. The unit also provides space stabilization of the antenna, B-sweep, and PPI-sweep, and generates the horizon line positioning signals that are sent to the indicator control.

LRU 5 - The Radar Transmitter genereates both the pulsed RF energy at the required pulse width and repetition frequency and the basic timing signal (radar trigger).

LRU 6 - The Power Supply provides DC power and appropriate switching action to various parts of the radar set.

LRU 7 - The Antenna Control (Servo assembly) generates signals that control antenna, B-sweep, and elevation strobe position. It also generates the simulated composite angle error signal for BIT 3.

LRU 8 - The Monitor Control contains switches for BIT, meter, stabilization control, and VC scale factor selections. Switches for selection of radar voltages and current to be read on the monitor meter are also available. Prominently displayed are indicator lights to warn of CORDS malfunction during either BIT or CORDS operation and of overheating within the radar set (CORDS capability has been deleted in later equipment.



VOLUME (CU FT)	WEIGHT (LB)	INPUT POWER (WATTS)	PARTS COMPLEMENT				
			INTEGRATED CIRCUITS	SEMI-CONDUCTORS	TUBES	PASSIVE	TOTAL
-	637		172	2920	24	10, 437	13, 553

Figure 6. AN/APQ-120 Airborne Fire Control Set

LRU 9 - The Radar Set Control enables the operator to select power, mode, and function. An Indicator light indicates when the radar has attained a skin track condition.

LRU 10 - The Antenna Control contains controls for azimuth positioning, range strobe, range flag, acquisition symbols, and elevation positioning of the antenna. It also provides lock-on and target reject capability, adjustment of the antenna at boresight for air-to-ground ranging, and ground adjustment of azimuth and elevation boresight potentiometers for air-to-ground operations.

LRU 11 - The Indicator Control accepts signals from other units and associated equipment within the radar set and performs the signal reshaping and switching required to provide signal voltages and scale factors for displays on the indicators. It also develops the deflection and intensity signals for the indicators.

LRU 12 - The Forward Indicator is a combination azimuth-elevation-range indicator and optical display unit. Airborne intercept, mapping, and bombing information are displayed on the indicator and, with the track display, enables the pilot to direct the aircraft on the correct course for firing air-to-air missiles.

LRU 13 - The Aft Indicator provides the same displays as the forward Indicator, but does not include an optical display unit.

LRU 14 - The Electrical Equipment Rack supports all the components that make up the radar nose package and contains a built-in amplifier assembly to heat the rate gyro assemblies.

LRU 15 - The Cable Assembly connects aircraft wiring from the forward bulkhead to the radar nose package. At the field shop it connects the test bench set to the forward radar assembly.

LRU 16 - The Antenna provides for the transmission and reception of RF pulses and rate position information for computing, angle tracking, and display. During an attack, antenna movement rate and position signals are used for computing and displaying aircraft steering information and for computing missile launch signals.

LRU 17 - The Electrical Synchronizer develops the basic tracking video signals for the computer, servo tracking loop, and the indicators. Output voltages are fed to the computer for attack course computation. Also developed by the synchronizer are the required range gates for angle tracking, air-to-ground, AGC circuits, and for positioning the range strobe symbol.

LRU 18 - The Oscillator Control provides a command signal to a servo amplifier to run the magnetron tuner assembly.

LRU 19 - The Waveguide Assembly combines the RF output of the radar transmitter with the output from the CW KPA so that both can apply power to the antenna. In test operation, the antenna is bypassed and the RF energy is directed to a dummy load.

LRU 20 - The Power Supply provides regulated -600 V and +900 V for the pump tube.

LRU 21 - Output from the Radio Frequency Oscillator (pulse STALO) is used as the radar set frequency reference in the CORDS mode.

LRU 22 - The Range Indicator provides range and range-rate information during visual identification operation.

c. Aircraft Installation

The physical placement of the APQ-120 radar LRUs aboard the F-4E aircraft is shown in Figure 7.

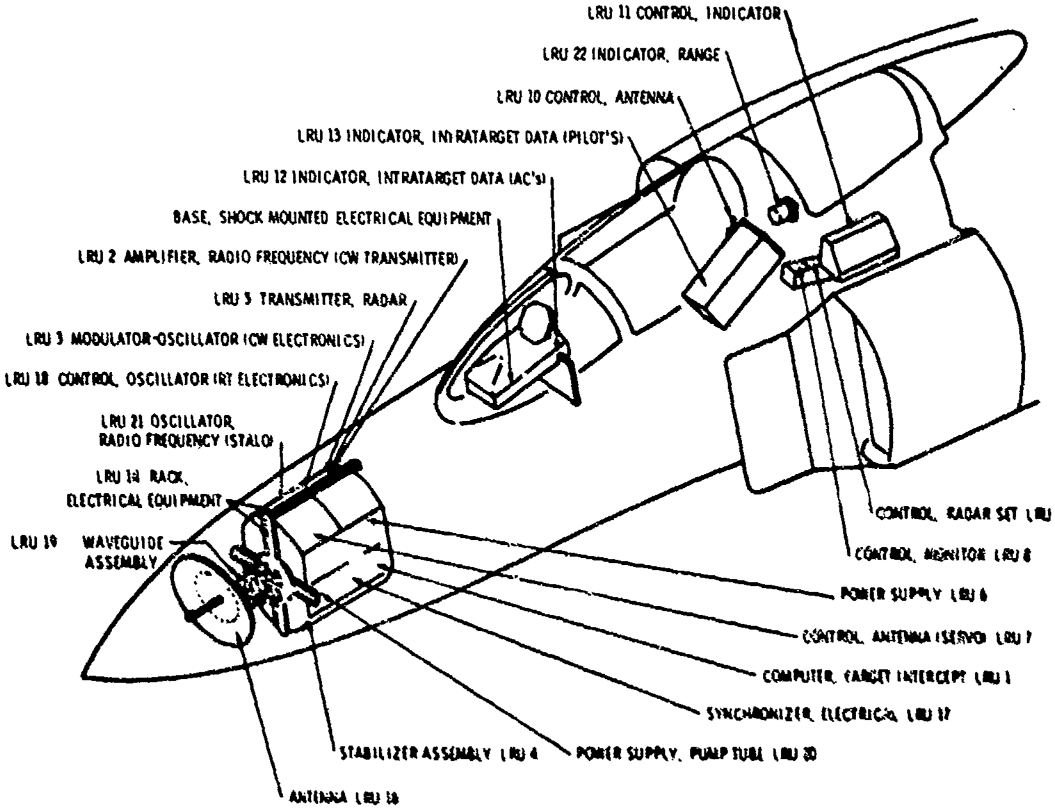


Figure 7. Installation APQ-120

G. DATA ANALYZED AND PLACES VISITED

This study was conducted in four primary phases - familiarization, data acquisition, analysis, and report.

During the familiarization period, several visits were made to Griffiss Air Force Base, which, being nearby, afforded early opportunity to become familiar with Air Force reporting and maintenance procedures and the 66-1 data system. Table II shows the Air Force Bases and Depots visited for data familiarization and acquisition.

Concurrently, visits were made and data obtained from ASD/SD4E-5 in reference to the APQ-120 contract phasing, delivery requirements, reliability program and design requirements. The data obtained is identified in Table III. In parallel, General Electric acquired and organized the in-house data required for the analysis of the APQ-113/114/144 radars, during the pre-release and the factory cycles. Table IV identifies the data used.

Platform and field data obtained directly from both prime contractors, General Dynamics and McDonnell Douglas, via the SPO, and from AFLC, is reflected in Tables III and IV along with data obtained directly from operational bases and maintenance depots (WRAMA & OOAMA). Table II identifies locations and functions contacted and Tables III and IV the specific data sources. Table V provides general data applicable to all the radars studied.

TABLE II. FIELD DATA FAMILIARIZATION AND ACQUISITION

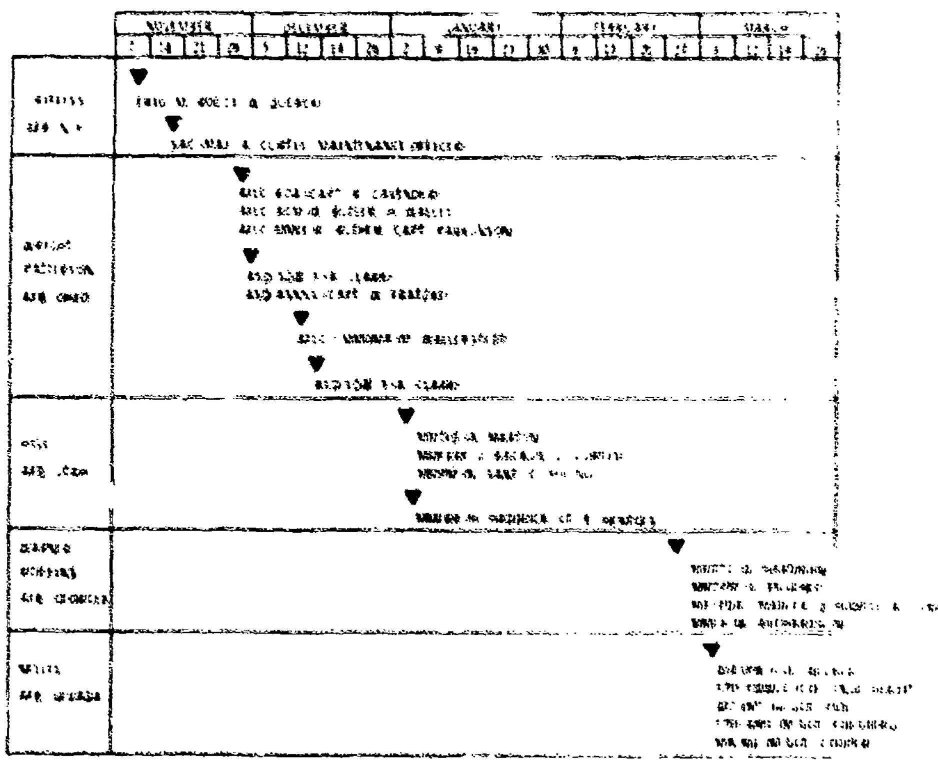


TABLE III. APQ-120 DATA

REPORT	SOURCE	EQUIPMENT & TIME PERIOD
PRERELEASE		
SPECIFICATION CONTROL DRAWING (53-870050)	MCDONNELL/DOUGLAS	APQ-120 (JAN 1966)
ENVIRONMENTAL DESIGN REQUIREMENTS (8738)	MCDONNELL/DOUGLAS	APQ-120 (APR 1962)
RELIABILITY ANALYSIS ESTIMATE (6686A)	WESTINGHOUSE	APQ-120 (MAR 1967)
RELIABILITY DEMONSTRATION TEST (FINAL REPORT) (S14128)	WESTINGHOUSE	APQ-120 (OCT 1971)
PLATFORM		
MAINTENANCE ACTIONS & PARTS PERFORMANCE SUMMARY	MCDONNELL/DOUGLAS	F-4E/APQ-120 (1968 - 1970)
FIELD		
PRODUCT IMPROVEMENT ANALYSIS (C05-01-1-1103)	ARINC	APQ-120 (MAR 1971)
MAINTENANCE REPORT (RCS 6 LOG K 261)	USAF AFLC	F-4E/APQ-120 (JUN 1971 - NOV 1971)
MAINTENANCE ACTIONS (RCS 5 LOG K 261)	USAF AFLC	F-4E/APQ-120 (NOV 1970 - NOV 1971)
MAINTENANCE REPORT	USAF AFLC	F-4E (JAN 1969 - JUL 1969)
MONTHLY MAINTENANCE ANALYSIS (RCS TAC K10) (BK I, II & III)	USAF NELLIS	F-4 & F-111 (1971)
RELIABILITY REVIEW MEETINGS (2)	USAF AFLC HQASO	APQ-120 (APR & SEP 1971)
ECP/ECN	WESTINGHOUSE/MCAIR	APQ-120 (1969 - 1971)
MATERIAL PERFORMANCE PACKAGE (0071 MPP 020A)	USAF OGDEN AMA	APQ-120 (MAY 1971)
CONFIGURATION LIST	USAF 1ST TFW	APQ-120 (AUG 1971)
INCREASED RELIABILITY OF OPERATIONAL SYSTEMS (IROS)	USAF AFLC	ALL AIR FORCE AIRCRAFT (1970)
RELIABILITY REVIEW	USAF AFSC (COL B BRIGHT)	APQ-120 (1970)
VIBRATION & ACOUSTIC MEST: ON AN RF4C A-C (TM-SES/67-4)	USAF AFSC ASD (SEG) (E DREHER & R SEVY)	1967
STRUCTURAL DYNAMICS (4236-2912 & 4236-4100)	MCDONNELL/DOUGLAS (D VOLKER)	F-4E
A-C TEST REPORT VIBRATION SURVEY (REPORT 68-389)	MCDONNELL DOUGLAS (R WHEELER)	RF4B/C
F-4E ABORT ANALYSIS	NELL AFB	F4-E 1971 3RD QTR
LIFE CYCLE COSTS		
LOGISTICS SUPPORT COST RANKING (K 251)	USAF AFLC	APQ-120 (JUL 1971 - SEP 1971)
A-X 12 YR OPERATIONAL & SUPPORT COST MODEL (MEMO 424)	USAF AFLC (CAPT R CAVENDER)	F-4E (MAR 1971)
COST OF OWNERSHIP STUDY	USAF AFSC ASD (CAPT R DOLAN)	APQ-120 (AUG 1971)

TABLE IV. APQ-113/114/144 DATA

REPORT	SOURCE	EQUIPMENT & TIME PERIOD
PRE-RELEASE & FACTORY		
TEST REPORTS	GE FAILURE REPORTING SYSTEM	APQ-113 RDT&E PROGRAM (1965-1967) APQ-113/114/144 PRODUCTION ('67 - '71)
SYSTEM TEST LOGS	GE MICROFILM FILE	APQ-113 (FEB 1966) APQ-114 ↓ APQ-144 (JAN 1971)
ENGINEERING QUAL TEST REPORT	GE DESIGN ENGINEERING	APQ-113 (JUNE 1966) APQ-114 (JUNE 1968) APQ-144 (JUNE 1971)
EQUIPMENT SHIP SCHEDULE	GE PROGRAMS OFFICE	APQ 113 (1965) APQ 114 ↓ APQ 144 (1971)
MANUFACTURING PLANNING RECORDS	GE MANUFACTURING PLANNING	APQ-113 (1965-1967)
EQUIVALENT SYSTEM COMPLEXITY FACTORS	GE R&QA, MFG T/T, MFG. FINANCE RECORDS	APQ-113 (1965-1967)
RELIABILITY TESTING PROGRAM	GE RELIABILITY ENGR (D.M. DAVIS)	APQ-113 (SEPT 1965)
PRE-QUAL REL TESTS (2)	GE RELIABILITY ENGR (D.M. DAVIS)	APQ-113 (AUG 1965-JAN 1966)
REL QUAL TEST (RET)	GE RELIABILITY ENGR (D.M. DAVIS)	APQ 113 FINAL REPORT (APR 1965)
PRELIMINARY & PRESENT CARRY-ON RELIABILITY PROGRAM	GE RELIABILITY ENGINEERING (S.G. MILLER)	APQ-113 RDT&E PROGRAM PLAN (JAN 1966)
REL. TEST ANALYZE AND FIX PROGRAM (TAAF)	GE RELIABILITY ENGR.	APQ 114 FINAL REPORT (NOV. 1968)
PERFORMANCE/DESIGN & PRODUCT CONFIGURATION REQUIREMENTS (FZE-00003E)	GENERAL DYNAMICS	APQ-113 (AUG 1966)
VENDOR RATING SYSTEM	GE R&QA SUPPLIER RATING SYSTEM	APQ 113 (1967-1969) APQ 114 (1967-1970) APQ-144 (1970-1971)
LRU BURN-IN REPORT SUMMARY	GE R&QA DATA SUMMARY	APQ 113/114/144
COST MODULES	GE COST ESTIMATING	APQ 113/114/144 (1966-1971)
RELIABILITY ACCEPTANCE TEST (RAT) FINAL REPORT	GE REL. ENGR.	APQ 113 PRODUCTION LOT #1 (APR 1969) & PRODUCTION LOG #2 (OCT 1969) APQ 114 (SEP 1970) APQ 144 (JUN 1971)
RELIABILITY PREDICTION REPORT	GE R&QA PREDICTION REPORT SYSTEM	APQ 113 (OCT 1963) APQ 113 (JAN 1969) APQ 114 (SEP 1970) APQ 144 (JUN 1971)
PLATFORM		
QUALITY ASSURANCE DEFICIENCY REPORTS (QAD-B)	GENERAL DYNAMICS INCOMING & AIRCRAFT FAILURES	APQ 113-114-144 (1966-1971)
PRODUCT SERVICE CUSTOMER REPORTS	GE CUSTOMER ENGR. (TECH REPS AT GE-FW) GENERATED AT SRA-FW	APQ 113-114-144 (OCT 1966-DEC 1972)
FIELD		
MAINTENANCE REPORT (RCS 6 LOG K 261)	USAF AFLC	APQ 113 (F-111A & E) APQ 114 (FB-111A) (JUN 1971-NOV 1971)
MAINTENANCE ACTIONS (RCS 5 LOG K 261)	USAF AFLC	APQ 113 (F-111A & E) APQ 114 (FB-111A) (NOV 1970-NOV 1971)
VIBRATION MEASUREMENTS FOR F111A WEAPON BAY GUN FIRING DURING SUBSONIC & GROUND TESTS (FZS-12-1006)	GENERAL DYNAMICS	F111A 30 DEC 1967
VIBRATION MEASUREMENTS DURING WEAPON BAY GUN FIRING SUBSONIC AND SUPERSONIC FLIGHT (A/C #5) (FZS-12-1026)	GENERAL DYNAMICS	F111A APQ 113 15 AUG 1968
VIBRATION & ACOUSTIC MEASUREMENTS ON F111A CLEAN AIRPLANE IN LEVEL FLIGHT (A/C #75) (FZS-12-121)	GENERAL DYNAMICS	F111A APQ 113 15 MAR 1971
MATERIAL STANDARD (G034)	USAF WRAMA	[illegible]
EQUIPMENT MASTER STOCK NOS (D041)	USAF WRAMA	[illegible]
MONTHLY MAINTENANCE ANALYSIS (RCS TAC X38) 300K [illegible]	USAF NELLIS	[illegible]
BASE MATERIAL CONSUMPTION BLIS (PCN N11400?)	USAF NELLIS	[illegible]
SYSTEM RELIABILITY REPORT (RCS LOG K 271)	USAF SMAMA	[illegible]
CANNIBALIZATION DATA	USAF NELLIS	[illegible]
INCREASED RELIABILITY OF OPERATIONAL SYSTEMS (IROS)	USAF AFLC	[illegible]
SYSTEM EQUIPMENT PERFORMANCE DATA	USAF AFLC	[illegible]
CATEGORY II EVALUATION OF AN F111A AIRCRAFT IN THE CLIMATIC LABORATORY TROPICAL, ARCTIC & DESERT ENVIRONMENTS (TR 68-?)	USAF [illegible]	[illegible]

TABLE V. APQ-120/113/114/144 GENERAL DATA

REPORT	SOURCE	EQUIPMENT & TIME PERIOD
GENERAL PUBLICATIONS		
PRODUCT PERFORMANCE (AFLC 66-15)	USAF AFLC	(FEB 1970)
TRAINING PRODUCT PERFORMANCE (PART I, II & III) (66-1)	USAF AFLC AFM	(JAN 1970)
FORWARDS (LOG K 260, K 261, K 262)	USAF AFLC	(DEC 1971)
MAINTENANCE DATA/LOGISTICS MANAGEMENT (AFLCP 50-3)	USAF AFLC	(OCT 1963)
WORK UNIT CODE MANUAL (TO)	USAF AFLC	F111A, F111E, FB111 & F4E (JUL 1971)
ILLUSTRATED PARTS BREAKDOWN (TO)	USAF AFLC	F111A, F111E, FB111 & F4E (1971)
LOGISTICS SUPPORT COST RANKING (K 051)	USAF AFLC	APQ-113/114 (JUL 1971 - SEP 1971)
RELIABILITY TESTS: EXPONENTIAL DISTRIBUTION (MIL-STD-781B)	US DOD	ALL PROGRAMS (NOV 1967)
RELIABILITY & LONGEVITY REQUIREMENTS FOR ELECTRONIC EQUIPMENT (MIL-R-26667A)	USAF	ALL PROGRAMS (JUN 1959)

SECTION II

RELIABILITY DISCIPLINES AND VALUES

A. INTRODUCTION

This section is analytical in content and describes the modeling approaches used in dimensioning reliability program elements and values based on APQ-113 radar experience. The relationships established, for the examples analyzed, are expressed in general terms so that they may be tested over an extended data base utilizing other sources.

The section is introduced with a discussion of the origin and development of the Reliability Planning and Management (RPM) model. The purpose is to provide the framework for the following analysis of the reliability growth rate (alpha, α) as well as for the modeling presented to quantify the value of reliability investment.

B. SUMMARY

1. RELIABILITY PLANNING AND MANAGEMENT (RPM)

The background and development of this methodology is described and explained. The need and advantage of the application of this methodology to future programs are presented. The relationships of "prediction versus requirement," "product capability," "environmental exposure," and "growth rate" are defined.

2. RELIABILITY GROWTH RATE

The analytical derivation of alpha (α) is treated with consideration and emphasis on timely removal of systematic failures, distribution of failure mechanisms, efficiency of corrective action, and equipment growth monitoring. The effect of quality of materials and stress factors is discussed. An analytical determination of parameters affecting the value of alpha is provided.

3. RELIABILITY INVESTMENT ANALYSIS

Models are derived for the relationships between costs of reliability test investment and equipment life cycle maintenance. Elements comprising the APQ-113 RDT&E reliability program investments are dimensioned, and the costs and value of parts and product screening are analyzed.

C. RELIABILITY PLANNING AND MANAGEMENT (RPM) BACKGROUND

1. INTRODUCTION

The purpose of this subsection, as a prelude to this report, is to present the historical background and origin of Reliability Planning and Management because it represents a significant development in reliability methodology based on the APQ-113/114/144 program experiences which are analyzed in this report. RPM is a powerful reliability growth technique, which was derived and developed before this study by J.D. Selby and S.G. Miller of General Electric, and initially presented on September 26, 1970 at the ASQC/SRE Seminar in Niagara Falls, New York.

2. SUMMARY

Reliability Planning and Management is a reliability RDT&E program methodology that bridges the gap between the stated reliability requirement and the reality of the technical planning required to assure successful hardware implementation.

The major points learned through retrospect analyses of these experiences are as follows:

- Credible reliability predictions are achievable in equipment performance.
- New products typically perform "off the board" at 10% of the predicted MTBF capability.
- Reliability growth is real and projectable.
- Reliability hardware development can be dimensioned, disciplined, and managed as an integral part of functional product development.

The RPM methodology ties together the contract requirement, the design margin between the MTBF prediction and stated requirement, a projection of the initial "off the board" product performance, recognition of the reality of reliability growth, and a sized estimate of the program required and implementation options/tradeoffs available for successful implementation of contract requirements in development equipments.

3. CONCLUSIONS

- RPM is a management tool that will bridge the gap between inherent reliability and achieved reliability in a timely and orderly manner.
- RPM allows customer and contractor to structure a Reliability Plan to assure compliance to requirement.
- RPM clearly dimensions the magnitude of a test-and-fix reliability growth program prior to contract release thereby allowing cost tradeoff decisions.
- RPM provides an additional tool to contracting officers for proposal evaluation and effective procuring activity.

4. BACKGROUND

The Reliability Planning and Management methodology is an outgrowth of first-hand reliability experiences with fixed price development contracts in the early and mid-1960s, wherein GE learned to approach the reliability program requirements differently. Successful implementation in several new technically sophisticated programs proved this approach.

The methodology is based on earlier works of J.T. Duane in which he postulated that reliability growth is a fact based on positive and constant corrective action. This methodology was first applied at GE/AESD when early attempts to qualify the APQ-113 and demonstrate reliability requirements failed. The measured MTBF was, after a test length spanning several MTBFs, only 10% of predicted. This unacceptable performance resulted even though all required prerelease reliability disciplines, as presently identified in MIL-STD-785, had been incorporated. The primary disciplines were: parts screening of semiconductors, good derating criteria, and parts standardization.

Under contractual pressure to meet the reliability requirements, a decision was made to maintain the equipment on test in the demonstration environment and to correct all observed problems. This test-analyze-and-fix program was successful because the equipment reliability was achieved and provided the basis for development of the RPM (Reliability Planning and Management) methodology.

5. CRITERIA AND CONSTRAINTS

RPM methodology forces early recognition of certain factors and conditions in order to achieve growth within the timeframe planned and meet the reliability requirement. The application of this methodology requires only that the designer not violate the laws of physics and that technical requirements imposed are not "beyond-the-state-of-the-art." Successful program implementation requires that specific compliance be achieved for each of the following criteria.

a. Prediction versus Requirements

Prior to release, the design must be simplified and parts stress and screening levels must be adjusted until the prediction exceeds the requirement by 25%. This prediction must be based on technically established and credible failure rates.

b. Product Capability

A realistic appraisal must be made of the new or changed design, recognizing the inevitability of flaws which constrain initial performance to 10% of the inherent analytical prediction.

c. Reliability Growth Rate

The reliability improvement for complex equipment, when operating in the "intended use" environment is approximately proportional to the square root of the

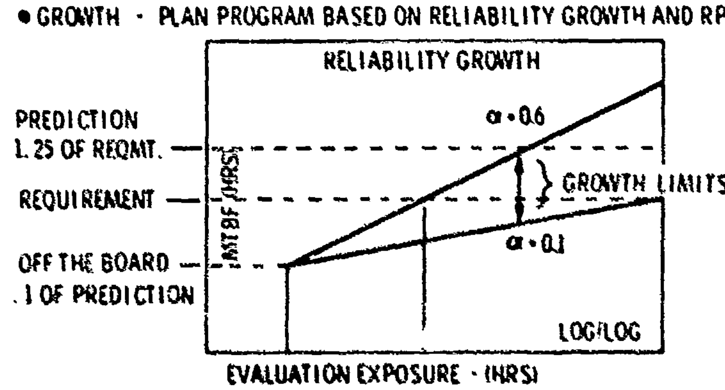
cumulative operating (test) time. For a constant level of corrective action effort and timely implementation, reliability growth closely approximates a straight line on log-log scales. Growth rates will vary depending on the effort expended. Factors impacting α growth rate are discussed in the following subsection entitled "Alpha Derivation." A rate of 0.5, which has been experienced, reflects a hard-hitting aggressive reliability program with management support spanning all functions of a knowledgeable organization. A minimum rate of 0.1 can be expected on programs where specific consideration is not given to or for reliability. In this latter case, growth is largely due to correcting the clearly obvious problems impacting production and implementing corrective actions as a result of user experience and complaints.

d. Product Environmental Evaluation Exposure

This structures the test evaluation time required to effect a compliant product based on initial capability and growth rate. Given the exposure hours and a valid assumption on achievable test efficiency (AESD uses 200 equipment exposure hours per calendar month for new complex avionics), the tradeoffs in program planning encompassing the acceptability of the initial design, design margin, number of equipments to be placed on test, facilities, test time, calendar time and program cost, can be objectively made by contractor and buyer.

The RPM model in Figure 8 shows the relationships of various growth rates and test times based on a 10% of prediction MTBF "off the board" performance.

- PREDICTION SIMPLIFY DESIGN UNTIL MIL-HDBK-217 PREDICTION MEETS REQUIREMENT WITH 25% MARGIN
- OFF THE BOARD DESIGN - PERFORMS AT 10% OF PREDICTED CAPABILITY
- SCREENING PROCESSING - ADJUST TO USE ENVIRONMENT
- GROWTH - PLAN PROGRAM BASED ON RELIABILITY GROWTH AND RPM TRADEOFFS



DIMENSIONS

- DESIGN QUALITY
- PRODUCT MARGINS
- INITIAL PERFORMANCE
- TIME - SCHEDULING
- RESOURCES OPTIONS
  - EQUIPMENTS
  - FACILITIES
  - CORRECTIVE ACTION EFFORT
- COST

Figure 8. Reliability Planning and Management

6. DEVELOPMENT (APQ-113)

RPM was developed based on the APQ-113 failure to demonstrate the required MTBF. This experience, supported by others, provided the basis for the RPM groundrules and disciplines that evolved. The following APQ-113 program experiences provided the baseline:

a) During the initial reliability evaluation test (Pre-Qual), the "off the board" measured MTBF was 9.5 hours at 90% LCL, or approximately 10% of the estimated reliability prediction. At that time the prediction was 88 hours and the evaluation test duration was 896 test hours.

b) Even after the equipment parts count was reduced, the percentage of screened parts increased, the LRU burn-in instituted, the initial test measured MTBF still amounted to only 10% of the revised 178 hour prediction. In order to meet the specified MTBF, an environmental LRU and radar reliability evaluation test program was initiated. The resulting equipment MTBF growth was exponential, approximating a straight line on log-log scales, and had a relatively steep (0.5) positive slope. RPM designates this slope, a measure of reliability growth, as alpha (α). This test program, which is depicted in Figure 9, continued for a total of over 10,000 test hours, resulting in measured equipment reliability performance meeting the specified MTBF of 137 hours.

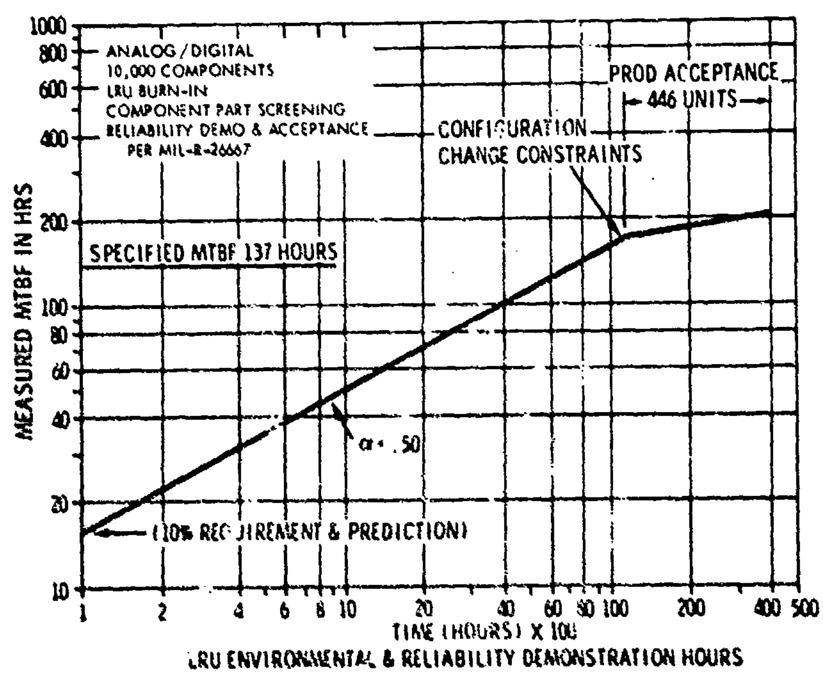


Figure 9. RPM Model

c) The reliability prediction for the final design of APQ-113 was estimated at 178 hours versus a contract requirement of 134 hours at 90% lower confidence level. The reliability requirement was achieved by demonstrating 152 hours at 90% lower confidence level. In this case, credible reliability predictions were achievable as evidenced by the reliability test results.

d) The reliability growth during the APQ-113 production phase was examined and is depicted in Figure 9 as an extension of the rate of reliability growth line observed during the APQ-113 evaluation test phase. Throughout the production phase of the APQ-113 program, a continuous formal Reliability Acceptance Test (RAT) was performed to assure maintenance of the required MTBF for each production lot. Fifty-four radars were subjected to 130 test hours each. The MTBF measured on the initial sample of equipments representing the first production lot was 196 hours, while the final measured MTBF for the total production quantity was 202 hours. This reliability performance, during the APQ-113 production phase, equates to a reliability growth rate (α) of 0.1. These results are to be expected however, since during production, the program is under the constraints of configuration control, which restrict the incorporation of equipment design improvements.

7. IMPLEMENTATION (APQ-114)

In 1967, General Dynamics requested modifications to the APQ-113 Attack Radar to meet the tactical requirements of the FB-111 bomber configuration. This new design, designated as the APQ-114 Attack Radar, required a 5% increase in the number of electrical component parts and a change to 20% of the existing electrical design, with no relief in the existing reliability requirements.

Taking full advantage of the reliability experience gained on the APQ-113, an APQ-114 reliability program was structured utilizing the concepts of RPM. For the first time GE/AESD implemented, from inception, a reliability program utilizing RPM as an integral part of the program plan, with the following constraints:

a) Dimensioning "Off the Board" MTBF

To dimension the off the board MTBF for a modified design, a reliability prediction analysis was performed. This prediction allowed for the changed portion of the design to initially achieve 10% of its analytical inherent prediction, while the balance of the design would be expected to achieve its predicted performance. This analysis indicated an off the board MTBF of 50 hours.

b) Although a growth rate of 0.5 was demonstrated on the APQ-113 program, it was difficult to estimate if a similar rate of growth could be sustained on a more complex product. It was therefore decided that a conservative estimate of 0.375 should be selected.

c) <u>Test Plan</u>

With the predicted off the board MTBF of 50 hours and a growth rate of 0.375, a reliability evaluation test program for a duration of 4000 hours was planned. The total test time would be accumulated on three advance manufactured radars, two maintained on tests concurrently, 24 hours per day, 7 days per week and the third radar to serve as an asset spare in support of the test to obtain maximum test efficiency.

d) <u>Test Findings</u>

The results of the reliability evaluation test program are portrayed in Figure 10 and indicate that the actual reliability performance exceeded predictions. A growth rate of 0.48 was achieved as compared to a predicted 0.375 and close to the 0.5 observed on the APQ-113 program, providing further evidence that a growth rate of 0.5 was realistic. Furthermore, the first lot of 84 APQ-114 Attack Radars manufactured, of which 21 went through Reliability Acceptance Test (RAT), measured an MTBF of 212 hours as compared to the 202 hours measured on the Production Radars of the mature APQ-113 program.

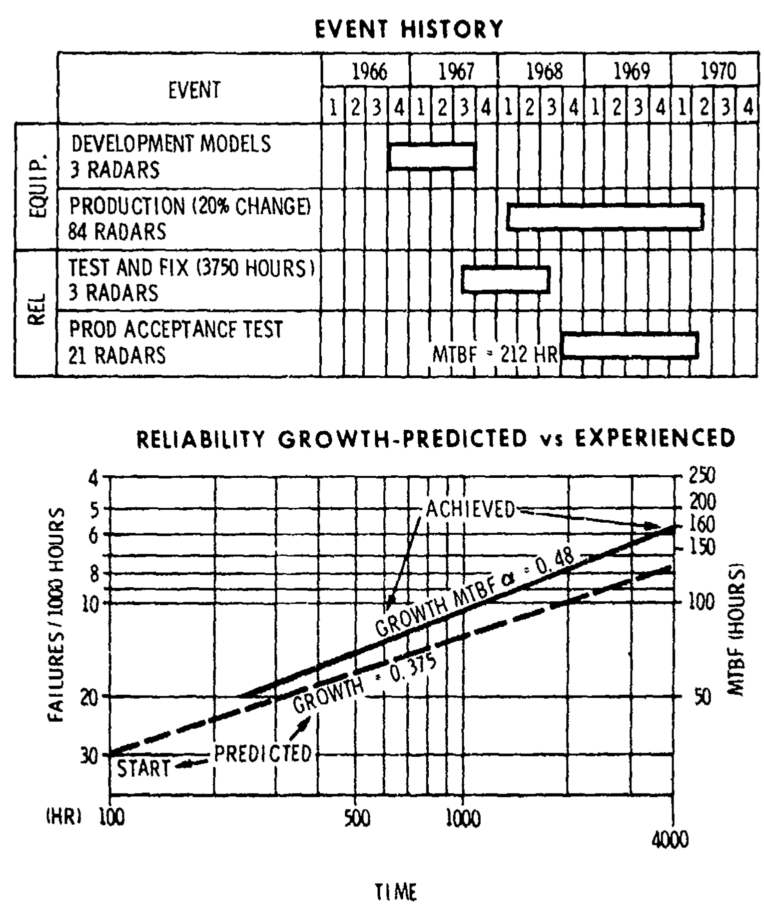


Figure 10. RPM Model

D. RELIABILITY GROWTH RATE - ALPHA (α) DERIVATION

1. INTRODUCTION

Reliability growth - α - is intrinsic to the RPM methodology, and is a necessary and important element in product development. Failure to provide the time and dollar resources necessary for reliability growth is an error committed much too often in RDT&E Program planning. In this section, the underlying mechanisms which influence α will be examined.

2. SUMMARY

The analytical derivation of alpha (α) is treated with consideration and emphasis on timely removal of systematic failures, distribution of failure mechanisms, efficiency of corrective action and equipment growth monitoring. The effect of quality of materials and stress factors is discussed. An analytical determination of parameters affecting the value of alpha is provided.

3. CONCLUSIONS

Alpha is influenced by:

a) The systematic and permanent removal of failure mechanisms through taking corrective action.

b) The rate and efficiency in failure removal.

c) The statistics of the underlying distribution of failure mechanisms whose failure rates prevent the initially released system from achieving its full potential.

Removal of every systematic failure mechanism from a uniformly distributed set of sources results in a growth slope of $\alpha = 0.6$. Removal of alternate failure mechanisms from the same source distribution causes a growth slope of $\alpha = 0.23$.

The use of tightly screened material (say, Class B, under MIL-STD-883) would have removed about half of the pattern problems in the APQ-114 RET test. This would result in a 40% increase in the initial MTBF, a drastic reduction of test time but no change in the growth rate.

The instantaneous growth slope can be infinite but the upper limit on α, the average growth curve slope, is 0.86.

α depends on the ratio $\bar{\lambda}/\sigma$, the ratio of the mean to the standard deviation of the distribution of failure sources.

α is independent of the cycle time to fix a failure, if the time is a constant multiple of M_s, the mean time between failure of a systematic failure mechanism. If the cycle time to fix each failure mechanism is different, as is usually the practical case, α depends strongly on the cycle time.

The ability to detect a problem is directly related to the ability of a particular test program to cause the failure mode to occur.

Data from the APQ-114 RET Program showed excellent agreement with the RPM model.

4. ALPHA DERIVATION

Figure 8 demonstrates that reliability growth, α, is a necessary and important element in product development. Furthermore, failure to provide the time and dollar resources necessary for reliability growth is an error committed much too often in RDT&E Program planning. In this section, the underlying mechanisms which influence α will be examined.

α is the average slope of the cumulative hazard rate curve, H(t), plotted on log-log paper, using a "best-fit" straight line. It will be shown later that α ranges from 0 to 0.86. Another statistic, α', will be used in this section; α' is the instantaneous slope of H(t). $|\alpha'|$ ranges from 0 to ∞.

$$H(t) = \frac{\text{total cumulative failures}}{\text{total time interval, 0 to t}}$$

Since α is the linear growth rate of MTBF with time when plotted on log-log scales, any factor which serves to increase M, or to speed an already apparent increase in M, will increase α. M is increased by the systematic and permanent removal of failure mechanisms, regardless of their sources, through taking appropriate corrective actions. α is affected by the characteristics of the underlying distribution of systematic failure mechanisms whose failure rates, λ_s, prevent the equipment initially released from achieving its full potential. α is also affected by the rate of failure removal, or efficiency in effecting corrective action.

The effects on α of the above three items will be treated in some detail.

a. Removal of Systematic Failure Mechanisms

Available data from industry and Figure 8 show conclusively that products initially released for manufacture exhibit a MTBF that is near 10% of the inherent, or latent, product capability predicted from parts performance. If M_p is the predicted MTBF, $M_p/10$ is the initial performance, and $10\lambda_p$ is the initial failure rate. Furthermore, regardless of the underlying failure distribution, the initial performance is evidently $M_p/10$. This fact implies that the underlying failure distribution is bounded, or constrained, such that the sum of the failure rates of all the systematic failure mechanisms which dilute equipment early performance and the non-pattern failures which one accepts and identifies as λ_p is $10\lambda_p$, i.e.,

$$\sum_{S=1}^{S=n} \lambda_s + \lambda_p = 10\lambda_p = \frac{10}{M_p}$$

Thus,

$$\sum_{S=1}^{S=n} \lambda_s = 9\lambda_p$$

These systematic, or pattern, failure mechanisms have an associated failure rate λ_s that is relatively "close to" the equipment failure rate λ_p, but which is several orders of magnitude above and, therefore, distinguishable from the failure rates of the parts themselves. (Figure 11) Note that the failure rate of the lowest major procurement assembly is approximately 10^{-5} compared to the systematic λ_s around 10^{-2}. The removal of these λ_s through an orderly and planned program of test, analysis, and corrective action, is one of the basic principles of RPM.

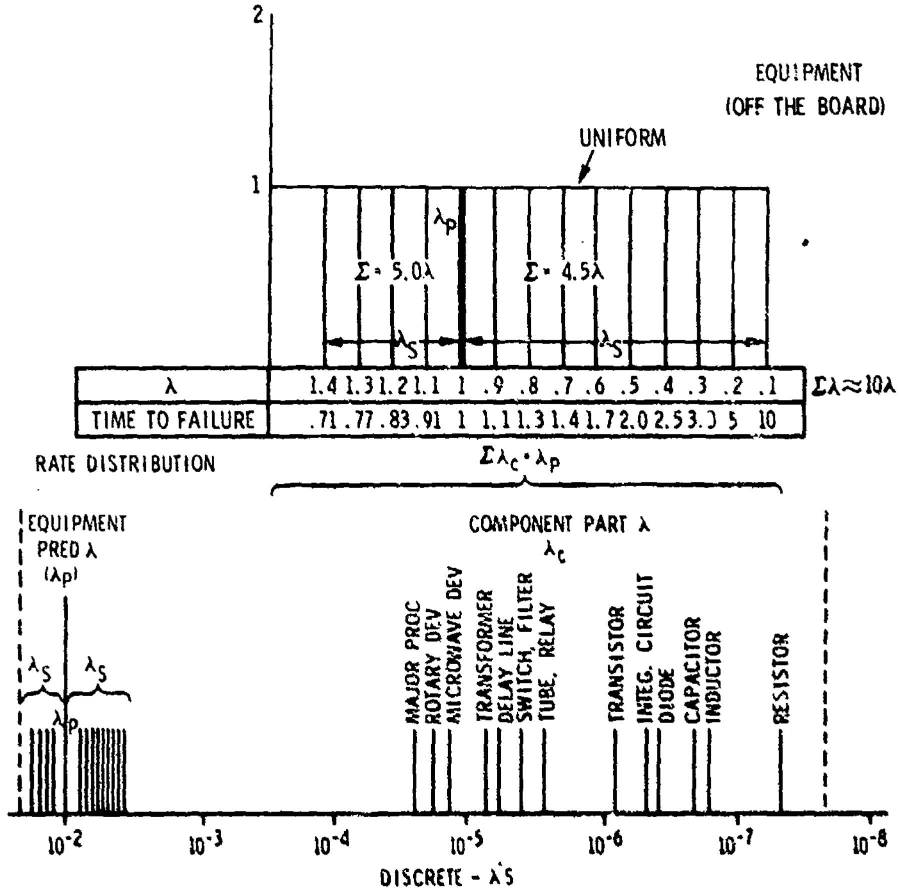


Figure 11. Failure Rate Distributions

Figure 12 is an idealized display of the λ_s which are close to the λ_p. The failures are placed regularly in time at intervals $M_s = 1/\lambda_s$ (when in reality they occur quite irregularly, even randomly in time, but such that their <u>average</u> interval of occurrence is M_s, determined by summing the times and failures from the s-th systematic failure mode). Also idealized in Figure 12 is the failure source distribution. It was assumed to be uniform and nearly symmetric about λ_p. These assumptions lead to no loss of

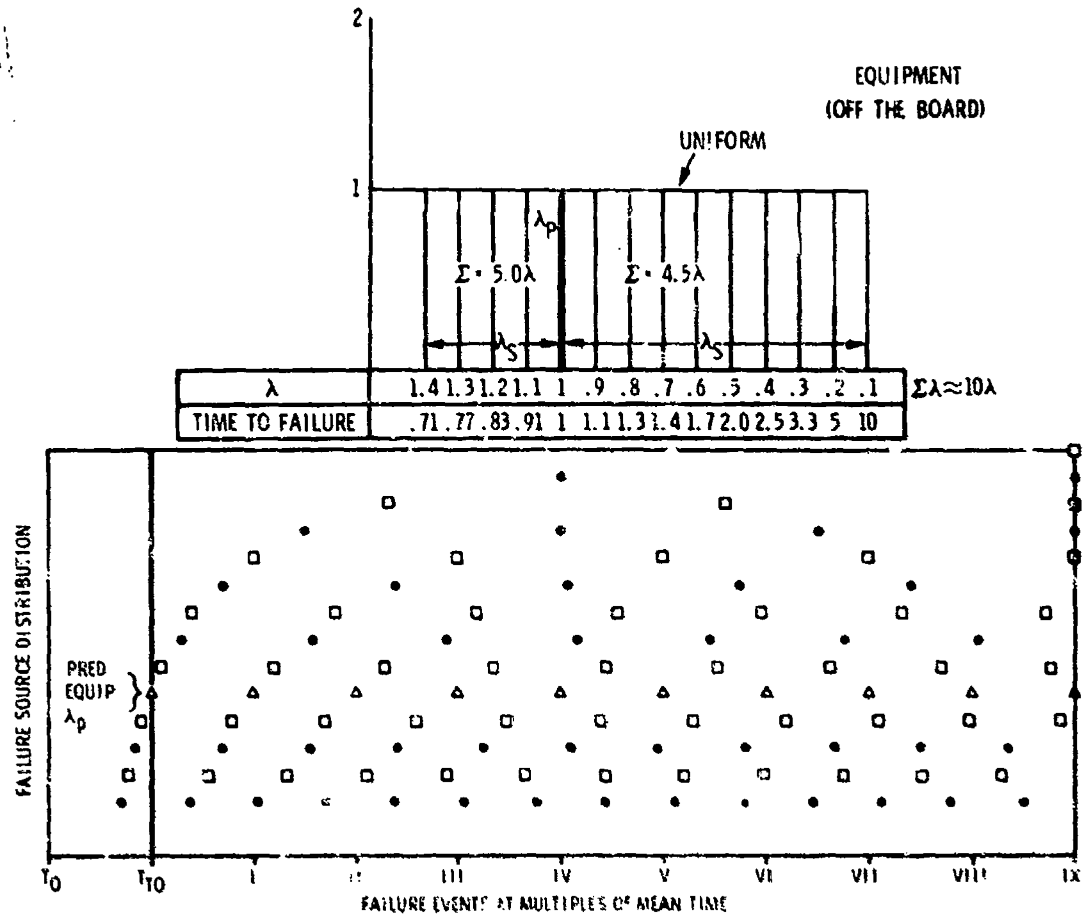


Figure 12. Model α Derivation

generality in the illustration, and subsequent paragraphs will discuss how the shape of the failure source distribution affects α.

In Figure 13, it was assumed that after the second occurrence of a failure, it was recognized as a repetitive, systematic, failure mechanism and was removed with corrective action. The cycle time to incorporate the corrective action was taken to be uniform at $2M_s$, that is, twice the MTBF of the systematic failure mechanism. Thus, the total cycle time from the first occurrence of each failure until corrective action becomes effective is $4M_s$, and assumed to be the <u>same for each</u> failure. If the rate of incorporating corrective action is <u>not</u> assumed to be the same for each systematic failure source, then α becomes dependent on cycle time. This relationship will be discussed subsequently.

If every systematic failure mechanism in the assumed uniform, symmetric distribution is identifiable and correctable and removed at a constant rate, the growth rate is $\alpha = 0.6$. Any inability (technical or time limitations) to effect identification and correction will, of course, constrain and reduce α. The rate of erosion of α can be seen by considering the case where only alternate failure mechanisms are fixed (half of them); the growth rate is reduced to $\alpha = 0.23$. (Figure 14) The cycle time to incorporate corrective action affects the break point of the curve λ(t), and thereby, the total test duration. In the above examples, the break point occurs precisely at $4M_s$ beyond the first failure of that mode with the shortest mean time, $M_{s\ min}$.

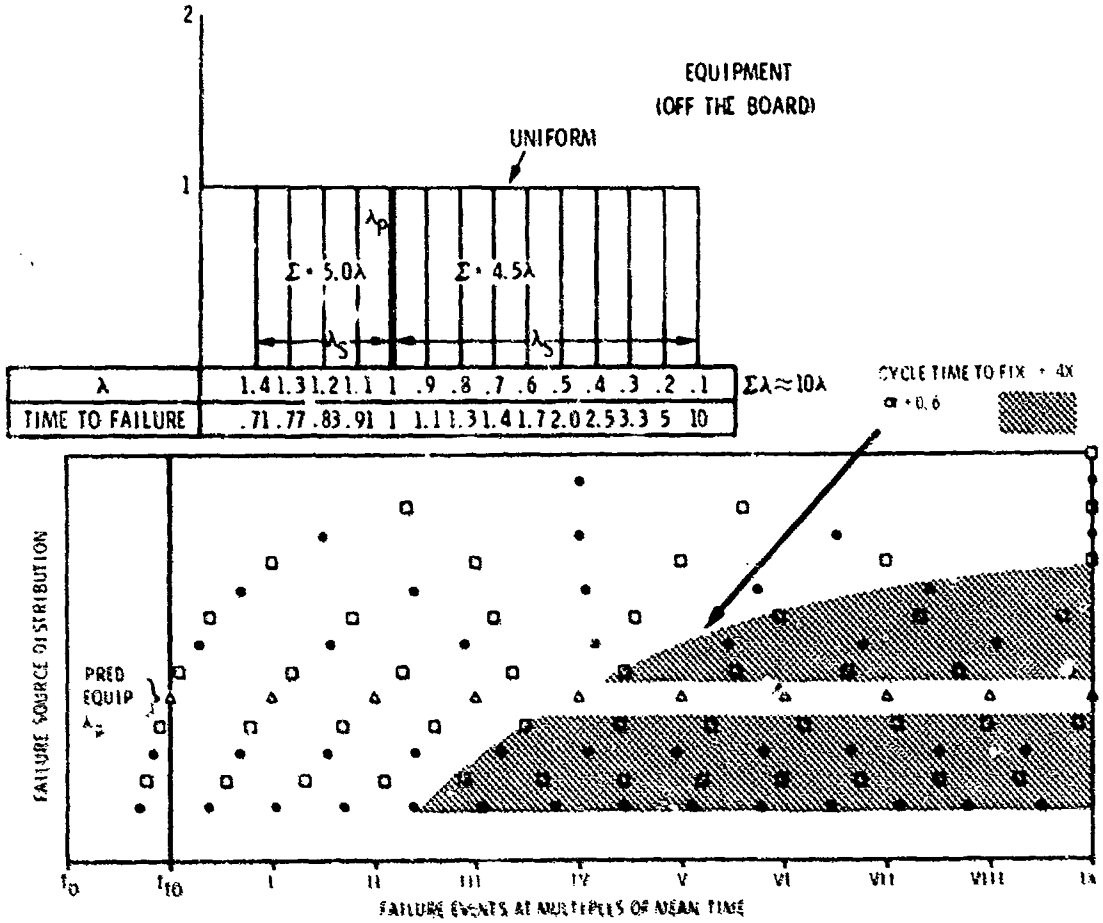
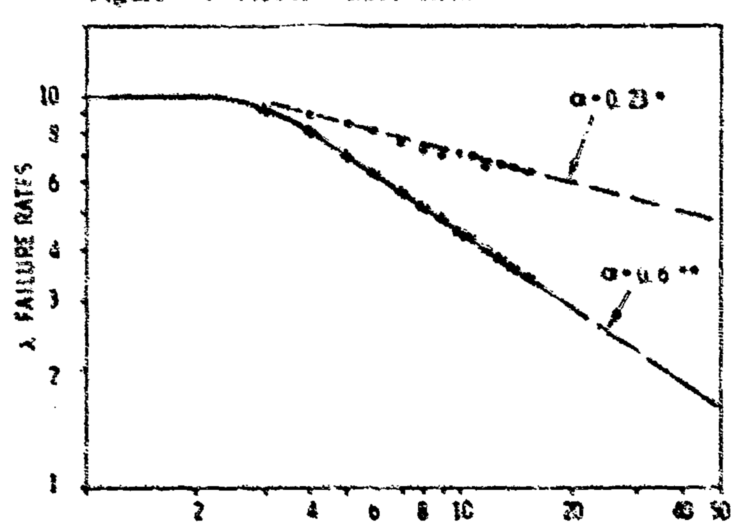


Figure 13. Model + Derivation



* FIX ALTERNATE FAILURES IN 4 Ms

** FIX EVERY FAILURE IN 4 Ms

Figure 14. Model + Portrayal

Figures 15 and 16 exhibit data from the APQ-114 RET Program, plotted in a form similar to Figures 12, 13, and 14 and showing excellent correlation with the postulated model. The 114 RET Program and its α growth will be discussed at the end of this section.

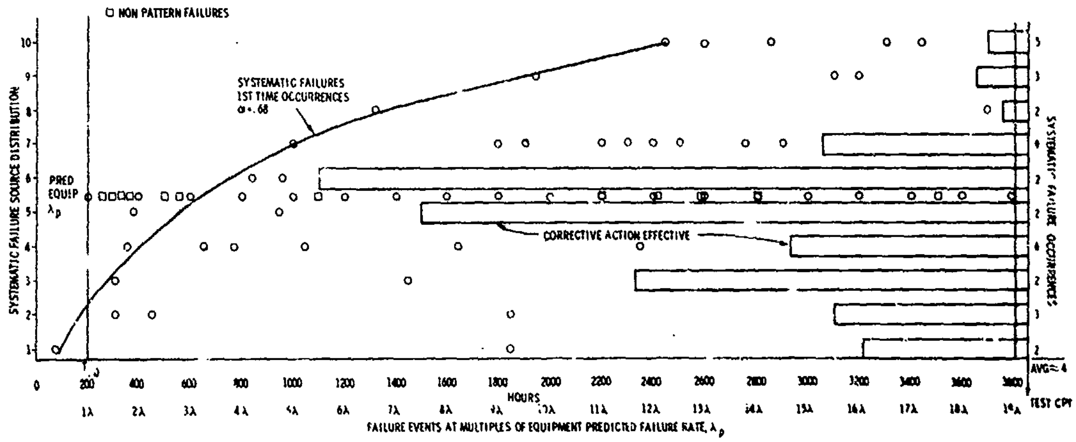


Figure 15. APQ-114 RET Results - Systematic Failure Sources

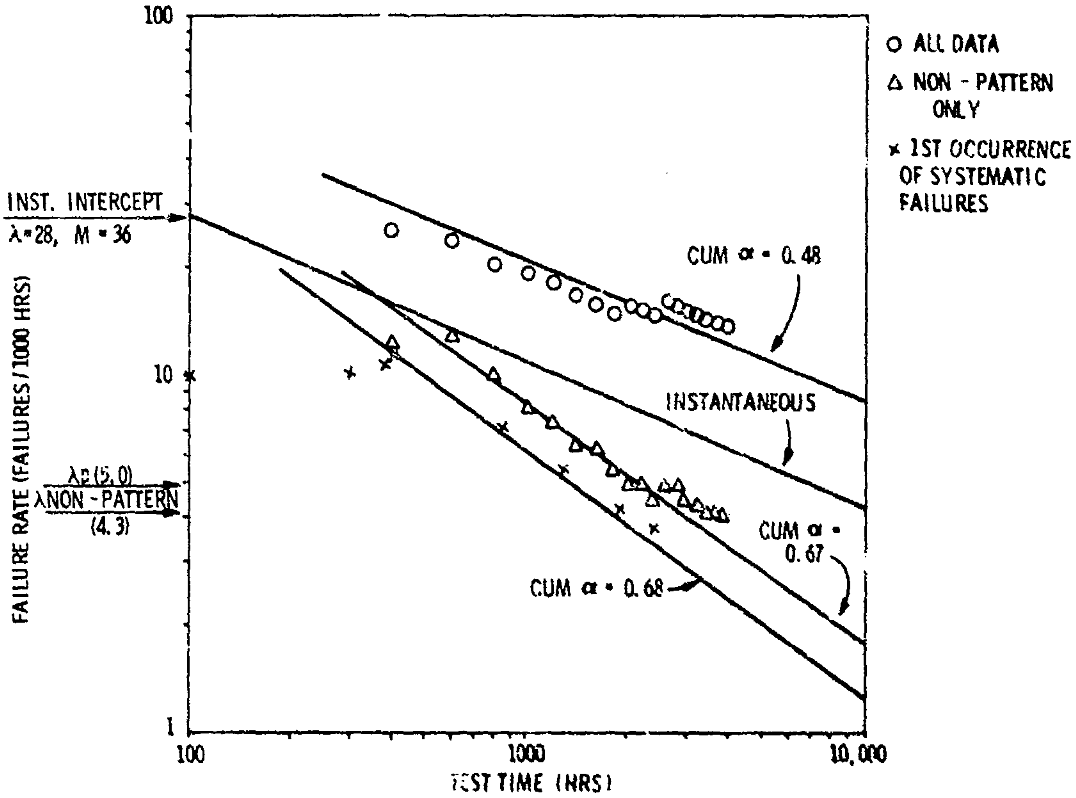


Figure 16. APQ-114 RET Program

b. Underlying Distribution of Failure Mechanisms

In the discussion above, the distribution of failure sources was assumed to be uniform, approximately symmetric about λ_p, and bounded by the constraint that

$$\sum_{S=1}^{S=n} \lambda_s = 9\lambda_p$$

In what follows, all distributions will be similarly bounded, since the preponderance of evidence confirms this constraint as factual, but variations in uniformity and symmetry will be discussed.

Intuitively, one can envision that there is no upper limit to α'. This observation comes from the following reasoning:

> Suppose the underlying failure distribution consisted of nine separate systematic failure mechanisms each with a failure rate $\lambda_s = \lambda_p$, and a mean time, $M_s = M_p$. If the nonsystematic failures associated with the predicted MTBF, M_p, are included with the systematics, the combined distribution satisfies the $10\,\lambda_p$ constraint but is plotted as a thin line at λ_p with n = 10 units high.
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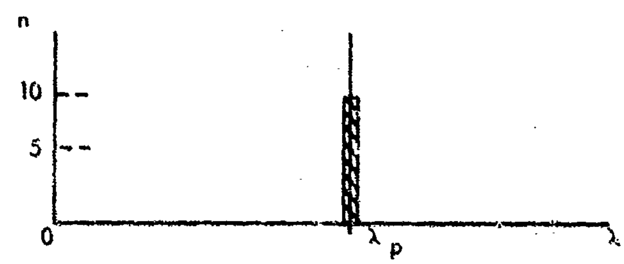
> 
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>
> Suppose also that the first failure of each of the systematic failure mechanisms occurs at exactly the same time, and that each is corrected in the same cycle time, say $4M_s$, as before. Then the $\lambda(t)$ plot, Figure 14, would be $\lambda = 10$ out to $t/M_s = 4$ and at that point jump discontinuously to $\lambda = 1$. Thus, the $\lambda(t)$ curve would be a vertical line at $t/M_s = 4$, and the slope of the instantaneous failure rate curve would be $\alpha' = \frac{dM}{dt} = \frac{-d\lambda}{dt} = +\infty$. The corresponding value for α is +0.860.

However, while theoretically α could approach 0.860, there are many practical factors which tend to limit the value of α:

1) Failure rates of pattern problems are distributed on both sides of λ_p.

2) The distributions are rarely symmetric.

3) Corrective actions are not always perfect.

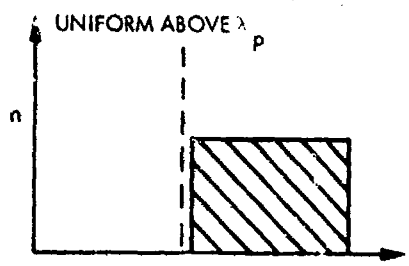
4) Failures do not occur at the same time.

5) The corrective action cycle time for each failure mechanism is really not the same.

6) Every failure cause is not discovered and eliminated.

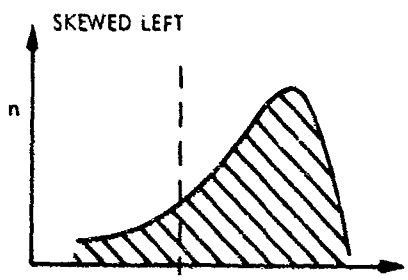
These "real-life" considerations have led GE to hypothesize a practically achievable upper growth limit of $\alpha = 0.6$, a number borne out by extensive GE/AESD reliability test data on a variety of different products.

Several skewed distributions were examined, and their associated values of mean, $\bar{\lambda}$, standard deviation about the mean, σ, and corresponding growth, α, are shown below normalized for $\lambda_p = 1$.



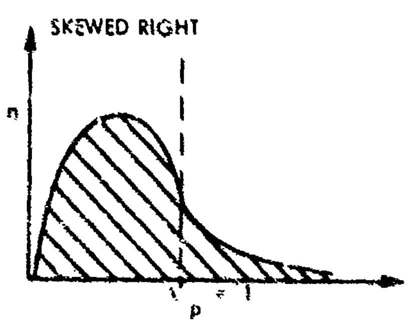
	$\bar{\lambda}$	σ	$\bar{\lambda}/\sigma$	α
(1)	1.29	0.223	5.78	0.74

NOTE: This case occurs when a number of failure mechanisms exist in the released design, any of which can unilaterally prevent the equipment from reaching its latent capability, M_p. It represents a design with shortcomings that are discovered early in test.



(2) 1.11 0.300 3.70 0.67

NOTE: This case occurs when the design contains a preponderance of easily detected failure mechanisms combined with a few subtle failure modes, which will not show up until far into test. This case occurs most frequently in "real life" experience



(3) 0.71 0.226 3.14 0.63

NOTE: This case occurs when the released design contains a high proportion of very subtle failure mechanisms, not easily detected in test. Few obvious faults exist. A long and discriminating test will be required to discover and remove these problems.

The distribution factors which work to increase α are:

1) Concentration of failure mechanisms near each other.

2) Failure mechanisms with λ_g above λ_p ($M_g < M_p$, leading to early discovery)

An inverse ralationship exists between the standard deviation, σ, of the assumed distribution and the value of α'. The smaller the σ (nearness of the MTBFs of individual failure modes to each other) the greater the α' (steeper rate of growth). In particular, the σ for the hypothetical case that gave $\alpha' = +\infty$ was zero. Subsection II. D. 7 examines this relationship with more rigor, and shows that α' depends on the ratio $\bar{\lambda}/\sigma$.

c. Efficiency in Effecting Corrective Action

In Part a. of this Subsection, it was assumed that the total cycle time to remove the s-th failure mode was fixed at $4M_s$. This assumption means that those failure mechanisms with low M_s which present themselves early and repetitively in test are fixed quite easily and rapidly, and those failure mechanisms with high M_s that occur only occasionally in test are from subtle sources, not easily discovered or corrected. Clearly, available experience confirms the reasonableness of this assumption.

However, the total cycle time to fix the s-th failure was reduced to $2M_s$ to obtain a comparison with the above result. α did not change, only the break point at which the $\lambda(t)$ curve began its descent from $10\lambda_p$ toward its asymptote, λ_p (Figure 14). Again, this break point was at $2M_s$ beyond the first failure in that mode with the shortest mean time, M_s. Thus, while the curves with $4M_s$ and $2M_s$ cycle times had the same α, and were parallel, the curve with the shorter cycle time reached the λ_p goal much quicker. Since test time increases logarithmically, the program with the shorter cycle time to fix failures requires less calendar time and test hours but more diligent corrective action.

Now if it is assumed that each of the failure mechanisms is eliminated in a different cycle time, the time to fix the failure becomes a variable that affects α - the shorter the fix-time, the steeper the α growth. Since this effect is quite irregular and related to the difficulty of the individual fix, its variable effect on α is best treated empirically using data from the actual case at hand.

The severity of the test environment is a factor which affects α in a subtle way since environmental severity can accelerate the exposure of failures. The optimum combination of temperature cycling, and/or long-term dwell at temperature pedestals in precipitating failure mechanisms is not addressed in this study. However, it is generally accepted that cycling is better where stress phenomena are involved (nailhead bonds in integrated circuits and solder joints, for example) while soaking at high temperature accelerates failure modes dependent on chemical processes and soaking at low temperature identifies circuit performance margins. Furthermore, available parts failure data confirm that high temperatures increase failure rates (Arrhenius Law).

Vibration, whether fixed frequency, swept sinusoidal, or random is known to expose mechanical weaknesses like wire dress problems, looseness of antenna linkages, incorrect torquing of screws, and general workmanship items. The time at which such failures occur is related to vibration levels through normal S-N Curves (Stress vs Number of Cycles).

In general, the ability to detect a problem is directly related to the ability of a test program to cause the failure mode to occur -- whether the causative mechanism is time duration (as in the case of wearout), environmental temperature, vibration, or combinations thereof.

d. Equipment Growth Monitoring

It is important to recognize that the RPM planning model expression

$$M_R = M_I\left(\frac{t_T}{t_i}\right)^{\alpha}$$

where

t_I = Time at which initial data point is plotted (pre-conditioning time)

M_R = MTBF required

M_I = MTBF initially

provides the test time, t_T, at which the instantaneous MTBF of the equipment under test will reach the MTBF requirement, $\overline{M_R}$. Normally, the cumulative MTBF is measured in test and converted to instantaneous MTBF by dividing by $1 - \alpha$. i.e.,

$$M_I = \frac{M_c}{1 - \alpha}$$

The cumulative MTBF is plotted vs cumulative test time, a straight line is fit to the data, and its slope α is measured. The instantaneous MTBF line is then drawn parallel to the cumulative line but displaced upward by an offset equal to $1/(1 - \alpha)$.

e. APQ-114 RET Program

Actual test data from the APQ-114 RET Program is shown in Figure 15 in a form similar to Figures 12 and 13 and in Figure 16. However, the ten most serious systematic failure modes are presented in order of ascending time to first failure. Thirty-six pattern incidents were grouped into ten failure modes uniformly distributed above λ_p. M_p for the APQ-114 was approximately 200 hours giving $\lambda_p = 0.005$ failure/hour. All the λ_s of the pattern modes were below λ_p, and it took several mean times, M_p, of test to precipitate failures and identify the modes as systematic. The 36 failures are the condensate of 130 separate test incidents resulting from the following censoring performed basically consistent with MIL-R-26667:

1) Test equipment failures were removed

2) Test operator errors were censored

3) Early mortality failures were removed

4) Confirmed wearout failures were removed if the wearout times exceeded that time contained in scheduled maintenance lists published prior to initiating RET.

In addition to the systematic failure mechanisms, 15 nonpattern parts failures occurred with their rate of occurrence largest in the first 700 hours of test. The λ of

these nonpattern, parts failures is 15/3500 = 4.3 fails/1000 hours compared with 5 predicted,indicating remarkable correlation between materials performance and prediction.

The summation of the λ_s associated with each systematic failure mode plus the λ associated with the 15 pattern failures were added to give a sum of 20.9 failures per thousand hours or a MTBF at test start of 48 hours, comparing reasonably well with the actual observed MTBF at the beginning of the APQ-114 RET program. This signifies that all the significant data that affected the RET results are in the above numbers.

The APQ-114 growth curves are plotted in Figure 16. The total data demonstrates a growth of $\alpha = 0.48$ and the instantaneous growth must be derived from the cumulative curve by offsetting it an amount

$$\frac{1}{1-\alpha} = \frac{1}{1-(.48)} = \frac{1}{0.52} = 1.92$$

The instantaneous curve is also shown in Figure 16, along with the growth for nonpattern failures.

The growth for nonpattern failures shows a remarkably interesting trend. The failure rate improves with test time at a steep growth rate ($\alpha = 0.67$) even though no specific corrective action was taken. Further, the growth persists for nearly 2000 hours and then levels off to a λ that is within 15% of the predicted, latent, λ_p. This improvement occurs even though an effort was made to recognize and censor early mortality failures from the data. This "apparent" growth, as distinguished from Duane growth resulting from correcting observed failures, has been noted in burn-in data in-house and has been reported by others in similar test work. True α growth contains a contribution from long-term burn-in as well as a contribution from correction and removal of failure mechanisms. One might expect the growth associated with the long-term burn-in to be less than the Duane growth due to the corrective activity in the latter case, but the 114 RET results do not confirm this expectation.

In any event, linear growth on log-log scales arises from a failure distribution that is Weibull in form. The phenomenon of part failures occurring at successively increasing time intervals is identified with the age of the equipment in test more than with the cumulative test time and, of course, benefits only the equipment under test, not all equipments of the same configuration.

The growth associated with the first time occurrence of each failure mechanism was also plotted in Figure 16. If it were ideally assumed that each failure mode was eliminated immediately after it first occurred, then the growth rate shown by this curve might be considered a theoretical upper limit on the Duane growth associated with identifying and eliminating all the pattern failures. In this case, $\alpha = 0.68$, and the actual test result of $\alpha = 0.48$ is substantially short of this empirically derived maximum.

5. QUALITY OF MATERIALS

The quality of materials has two basic effects on α-growth: one for pattern/correctable failures; a second, and different, effect on nonpattern/accepted residual/so-called "random" failures. The available APQ-114 and APQ-113 RET experience will be drawn on heavily in this empirical analysis.

a. Effect on α of Correctables

Of 51 incidents used in Duane growth curves, 36 are from identified pattern problems. Since many of the 36 incidents were repeated, they group themselves into 15 separate, correctable, pattern problems. The correction of these problems was the major contributor to the Duane growth of $\alpha = 0.48$ demonstrated on the APQ-114 Program. About half (actually 8) of these problems would not have existed if tightly screened material (equivalent to Class B under MIL-STD-883) had been used from the outset.

An additional two failure mechanisms might possibly have been eliminated under MIL-STD-883 Class B screening, but are not included with the above 8 since the problems were of a very subtle nature, uncovered only after many hours of concentrated testing and analysis. Eliminating these 8 failure mechanisms removes 19 incidents.

After removal of these 8 mechanisms the remaining 114 RET data then consists of 17 pattern failures from 7 correctable sources, plus 15 nonpattern problems. This data was replotted in a form similar to Figure 16. The growth rate was $\alpha = 0.48$ or identical to the growth using unscreened material, but the slope intercept was appreciably increased by the removal of material problems. In particular, the initial MTBF increased from an average of 42 to an average of 55 hours*, or an increase of 31%.

While this increase does not seem particularly dramatic of its own magnitude, it allows a tremendous shortening of test time and, therefore, cost-saving in test. With screened material, the same MTBF could be achieved in 1275 hours, for a saving of 2485 hours or 66% of the cost of test.

b. Effect on α of Nonpattern Problems

The "apparent" α-growth resulting from the tendency of nonpattern problems to occur at successively increasing times between failure was previously discussed and distinguished from Duane growth resulting from corrected causes.

The nonpattern part problems in both the 114 RET test and 113 qualification tests were all of the variety that conceivably could be eliminated (or reduced) by screening. The data from the 113 or 114 effort does not easily provide the desired data comparison, since these failures were not eliminated but accepted as the predicted residual. If all, or most, nonpattern failures were eliminated through the use of higher quality materials, the ultimately achieved MTBF clearly would be higher, and the "apparent" growth rate to get there would be lower than the 0.57 demonstrated in Figure 16. It is estimated that the α would be closer to 0.35.

*The word average is used to denote the average of two numbers obtained in extremely different ways: (1) The cumulative failure rate versus time was plotted in Figure 16, and a line faired through the data points. The instantaneous failure rate line was drawn parallel to the cumulative line but displaced downward by the offset factor $1-\alpha$ and extended to the left side intercept at $t = 100$ hours. The failure rate $\lambda_I = 28 \times 10^{-3}$ was obtained giving an initial MTBF of 36 hours. (2) The summation of all the systematic failure rates was taken, $\Sigma \lambda_s = 20.9 \times 10^{-3}$, and MTBF = 48 hours. The average of 36 and 48 hours was taken as the intercept.

Failure rate tables give a range for the improvement in the ultimate MTBF with improvement in parts screening levels. Experience with such data shows them to be reasonably accurate and credible (e.g., RADC Notebook II).

Actual in-house data from parts procured to MIL-STD-883 Class C, and on a later buy upgraded to the tighter screening requirements of MIL-STD-883 Class B, are shown in Table VI. The dramatic improvement in module and part failure percentages or percent defectives is at once evident. This table provides valuable data not readily available elsewhere. If projected costs of eliminating failures at each level of assembly can be hypothesized or determined, the table can be used to determine the cost effectiveness of screening to various levels under MIL-STD-883.

TABLE VI. PART FAILURE COMPARISON, MIL-STD-883 CLASS B AND CLASS C

		ICs	TRANSISTORS	SFPs**	DIODES	TRANSFORMERS	CONNECTORS	OTHERS*	TOTALS
MIL-STD-883 CLASS C	# FAILURES							QTY NOT	
	MODULE	447	441	251	178	7	N/A	SIGNIF	
	UNIT	55	38	101	50	4	2	23	
	EQUIPMENT	31	20	60	31	1	10	24	
	FIELD	1	1	3	1	2	3		
	TOTAL	534	500	415	260	14	15	47	1799
	# EQUIPMENTS	26	26	26	26	26	26	26	26
	#FAILURES/EQUIPMENT	20.5	19.2	15.9	10.0	0.5	0.6	1.8	69.2
	APPROXIMATE AVERAGE PART USAGE	2900	1690	260	5280	39	950	9400	20,519
	DROPOUT RATE	0.7%	1.1%	6.1%	0.2%	1.3%	0.06%	0.02%	0.3%
MIL-STD-883 CLASS B	# FAILURES							QTY NOT	
	MODULE	51	47	11	14		N/A	SIGNIF	
	UNIT	3	2	5	2		1	9	
	EQUIPMENT	2						3	
	FIELD						1	1	
	TOTAL	56	49	16	16	0	2	13	152
	# EQUIPMENTS	5	5	5	5	5	5	5	5
	#FAILURES/EQUIPMENT	11.2	9.8	3.2	3.2	0	0.4	2.6	30.4
	PART USAGE (APPROX.)	2900	1690	260	5280	111	950	9400	20,519
	DROPOUT RATE	0.4%	0.6%	1.2%	0.06%	N/A	0.04%	0.02%	0.1%

*OTHERS INCLUDE RESISTORS, CAPACITORS, CRYSTALS, COILS/CHOKES, INDUCTORS, DELAY LINES, AND MAJOR SUBCONTRACTOR ITEMS

**HYBRID MICROCIRCUIT

6. MANAGEMENT EFFECT ON ALPHA

Several basic effects of management commitments on α and on the overall reliability test have been observed in various test programs at GE. This commitment can take the form of multiple test positions, dollar resources, manpower commitments, production schedule incentives, priorities, or combinations thereof.

Multiple test positions accelerate accumulation of test time for minimum schedule within balanced limits of dollar expenditures for equipments versus dollar expenditures

for test time. Multiple test positions have very little effect on α, but large effect in shortening time and cost of the overall test. The remaining four factors cited above all serve to increase α and shorten the overall test within limits. Each factor works to limit the time between a failure occurrence and the ultimate corrective action in product to eliminate the cause, and in each case except priority, there is a saturation limit, or a diminishing return for the next unit of commitment. The optimization of the test cost factor in balance with the life cycle savings resulting from MTBF improvement has been treated elsewhere herein.

In the case of the APQ-113 Reliability Evaluation and Reliability Qualification Test effort which maintained an α = 0.48, the times to remove systematic failure mechanisms averaged 4.4 times the MTBF of the indicated failure mechanism. In the case of the APQ-114 RET Program, the α was slightly less (0.48), and the times to remove systematic failures were much shorter (4 times the MTBF). The reasons for the decreased α are:

1) Most of the failure mechanisms had been removed in the prior 113 design

2) There was only a 20% transition to the 114 design

3) The 113 production and quality learning was complete on 80% of the system.

The decrease in the average time to remove failure sources is related to experience, learning, and a greater propensity to investigate failure causes before the particular failure repeats in test.

Each of these RPM Programs had an adequate commitment of the above-listed management ingredients, necessary to program success.

7. ANALYTICAL DETERMINATION OF THE PARAMETERS AFFECTING THE VALUE OF THE SLOPE α'

a. Purpose of Analysis

The purpose of the analysis was to:

1) Identify and determine analytically, the parameters that affect the reliability growth rate α'

2) Determine if an upper bound on the value of α' exists

3) Determine the value of such an upper bound if one does indeed exist

b. Summary of Results

The parameter that primarily determines the value of α' is the ratio of the mean to the standard deviation of the probability density function (pdf) of the systematic failure mechanisms, $\bar{\lambda}_s/\sigma_{\lambda_s}$. Other influencing parameters are the symmetry of the

pdf and the number of standard deviations from $\bar{\lambda}_s$ to $\lambda_{s\ max}$. There is no theoretical upper limit on α', but as shown earlier, practical program factors tend to limit α' growth. It was also found that α' is not influenced by the time to detect and remove each failure mechanism if that time remains constant. Ways to increase the value of α' by judicious testing are discussed from a conceptual viewpoint.

c. Conditions of Analysis

The initial hazard rate λ_I of the equipment is equal to 10 λ_p, where λ_p is the inherent hazard rate of the parts comprising the equipment.

The final hazard rate of the equipment λ_F is equal to λ_p. This implies that the systematic failure mechanisms, which account for $9\lambda_p$, have been removed in the final state and only the inherent parts of the equipment can subsequently fail at a constant rate.

Each individual systematic failure mechanism is removed at four times its mean time to failure. That is,

$$t_{r_i} = 4/\lambda_{s_i}$$

where

λ_{s_i} = hazard rate of the i-th systematic failure mechanism

t_{r_i} = time to remove the i-th systematic failure mechanism measured from t = 0

The total hazard rate of the equipment $\lambda_T(t)$ is assumed to be a linear function of t on a log-log plot. For this analysis the linear characteristic will only be assumed, not proven.

The growth, α', is the negative instantaneous slope of a curve of failure rate versus time.

The computed value of α' is predicated on a line joining two distinct break points in a curve. α' is defined for

$$\frac{4}{\lambda_{s\ max}} \leq t \leq \frac{4}{\lambda_{s\ min}}$$

All early mortality defects have been removed by appropriately structured burn-in tests.

d. Results

The following listing contains the results of work reported under Analysis. All derivations are contained in that section.

1) The slope, α', of the hazard rate curve is as follows:

$$\alpha' = - \frac{1}{[\log (\lambda_{s_{max}}) - \log (\lambda_{s_{min}})]} \tag{7}$$

Since

$$[\log (\lambda_{s_{max}}) - \log (\lambda_{s_{min}})] \neq \log (\lambda_{s_{max}} - s_{min}),$$

α' depends not only upon the difference

$$(\lambda_{s_{max}} - \lambda_{s_{min}}),$$

(i.e., the spread of λ_s), but, more accurately, on the absolute values of

$$\lambda s_{max} \text{ and } \lambda s_{min}.$$

2) Not much insight into the process can be obtained from the above equation. For values of $|\alpha'| \geq 1.9$ the following expression approximates equation (7) above:

$$\alpha' \cong - \left[\frac{2.30}{k_1 (1 + s)} \left(\frac{\bar{\lambda} s}{\sigma_{\lambda_s}} \right) + \frac{1.15 (1 - s)}{(1 + s)} \right] \tag{18}$$

where $\bar{\lambda}_s$, σ_{λ_s}, and s are the mean, standard deviation, and symmetry parameter respectively of the λ_s probability density function. k_1 is the number of standard deviations from $\bar{\lambda}_s$ to $\lambda_{s\ max}$ or the parameter that measures the range, or spread, of the data.

3) If the λ_s pdf is symmetrical about its mean, $s = 1$ and equation (7) may be approximated as follows:

$$\alpha' \cong - \frac{1.15}{k_1} \left(\frac{\bar{\lambda} s}{\sigma_{\lambda_s}} \right) \tag{19}$$

for values of $|\alpha'| \geq 1.9$

4) Also when $s \approx 1$, the above expression shows that α' is directly related to the ratio of $\bar{\lambda} s/\sigma_{\lambda_s}$ and is inversely related to k_1. The value of k_1 is different for different pdf shapes. If the pdf type (or shape) remains constant, α' varies as the ratio $\bar{\lambda} s/\sigma_{\lambda_s}$.

5) Since

$$k_1 = \frac{\lambda_{s_{max}} - \bar{\lambda}_s}{\sigma_{\lambda_s}},$$

equation (19) above may also be expressed:

$$\alpha' \cong - \frac{1.15}{\left(\frac{\lambda_{s_{max}}}{\lambda_s} - 1\right)} \tag{20}$$

6) The maximum negative value of α' is infinity and occurs if

$$\sigma_{\lambda_s} = 0$$

or if

$$\lambda_{s_{max}} = \bar{\lambda}_s \cdot \sigma_{\lambda_s}$$

can conceptually be made zero by designing equipment with identical components (e.g., a box of only resistors), by selecting only those components with identical λ's, or by hypothesizing environmental stress factors which affect the failure mechanisms independently and cause all λ's to approach a single value.

7) The average value of λ_s governs the approximate mean time to discover and remove systematic defects, and thereby affects the length of test.

8) The time (t_0) to the first systematic failure mechanism removal is $4/\lambda_{s_{max}}$.

9) The time to the last systematic failure mechanism removal is $4/\lambda_{s_{min}}$.

10) The test time to achieve a specified reliability is governed by both $t_0 = 4/\lambda_{s_{max}}$ and α'.

c. Background

Systematic failure mechanisms are failure mechanisms that are designed and built into each and every equipment of a given design with certainty. These consist of design deficiencies, of engineering and drafting mistakes that went unnoticed, those manufacturing mistakes that are repeated (e.g., improper procedure), unreliable designs, and those repeated workmanship errors related to the above-mentioned mistakes and unforeseen or undimensioned material quality and screening constraint

either unique to a part or its application. Systematic failure mechanisms are distinguished from "random" defect failure mechanisms in that they can be removed from all the equipment of the same design once they are discovered in any one of the equipment. "Random" defect failure mechanisms can only be removed from the particular equipment under test.

It has been observed that complex electronic equipment of different design from different vendors have an initial λ_I of 10 λ_p. This, in effect, says that complex equipment with many possible sources of systematic failure mechanisms have initially on the average the same total $n_i \lambda s_i$. The individual $n_i \lambda s_i$ most likely are different, but their summation is not.

Thus,

$$\sum_{i=1}^{i=N_s} n_i \lambda_{s_i} = 9 \lambda_p$$

is a constant. No such constraint exists on the variance

$$\sigma^2_{\lambda_s}$$

or the type of probability density function.

f. Analysis

Define

$$\lambda_T(t) = \sum_{j=1}^{N_p} n_j \lambda e_j \sum_{i=1}^{N_s} n_i \lambda_{s_i}(t) = \lambda_p + \lambda_s(t) \qquad (1)$$

where

$\lambda_T(t)$ = total equipment hazard rate as a function of time

λe_j = hazard rate of the j-th part of the equipment

N_p = total number of equipment parts

$\lambda_{s_i}(t)$ = hazard rate as a function of time of the i-th systematic failure mechanism

N_s = total number of systematic failure mechanisms

n_j = number of parts having the j-th hazard rate

Initially at $t = 0$

$$\lambda_I = \lambda_T(0) = \lambda_p + \lambda_s(0) = 10\lambda_p \tag{2}$$

or

$$\lambda_s(0) = 9\lambda_p \tag{3}$$

$\lambda_s(t)$ decreases with time as the individual λ_{s_i} are removed. λ_p remains constant.

Define

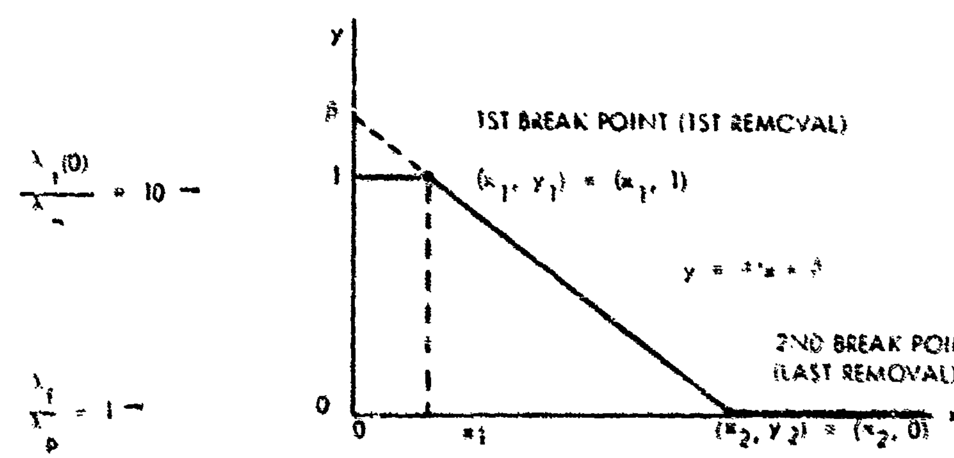
$$M_p = 1/\lambda_p = \text{equipment MTBF}$$

$$X = \log\left(\frac{t}{M_p}\right) = \log(t\lambda_p) \tag{4}$$

$$Y = \log\left(\frac{\lambda_T(t)}{\lambda_p}\right) \tag{5}$$

All logs are to the base 10.

Then



$$\alpha = \frac{Y_2 - Y_1}{X_2 - X_1} = \frac{0 - 1}{X_2 - X_1} = -\frac{1}{X_2 - X_1}$$

$$X_1 = \log\left(\frac{4\lambda_p}{\lambda_{s_{max}}}\right); \quad X_2 = \log\left(\frac{4\lambda_p}{\lambda_{s_{min}}}\right)$$

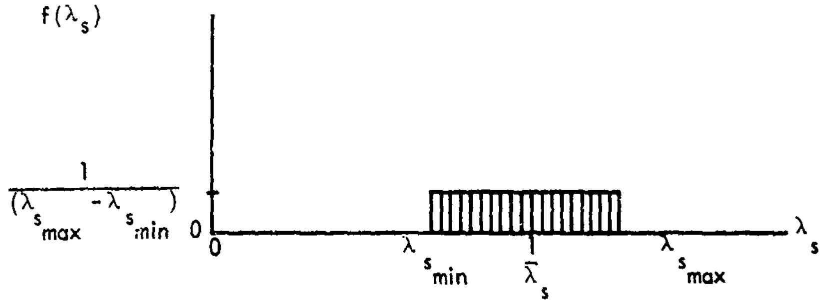
$$X_2 = \log(4\lambda_p) - \log(\lambda_{s_{min}})$$

$$X_1 = \log(4\lambda_p) - \log(\lambda_{s_{max}}) \tag{6}$$

$$X_2 - X_1 = \log(\lambda_{s_{max}}) - \log(\lambda_{s_{min}}) = \log\left(\frac{\lambda_{s_{max}}}{\lambda_{s_{min}}}\right)$$

$$\alpha' = \frac{1}{\log\left(\frac{\lambda_{s_{max}}}{\lambda_{s_{min}}}\right)} \tag{7}$$

As an example consider an equiprobable pdf as shown below:



$$\bar{\lambda}_s = \frac{\lambda_{s_{max}} + \lambda_{s_{min}}}{2}$$

$$\sigma_{\lambda_s} = \frac{\lambda_{s_{max}} - \lambda_{s_{min}}}{2\sqrt{3}}$$

It can be seen that

$$\lambda_{s_{max}} = \bar{\lambda}_s + k_1 \sigma_{\lambda_s}$$

$$\lambda_{s_{min}} = \bar{\lambda}_s - k_2 \sigma_{\lambda_s}$$

$$\sigma_{\lambda_s} = \frac{\lambda_{s_{max}} - \lambda_{s_{min}}}{2\sqrt{3}} = \frac{(k_1 + k_2)\sigma_{\lambda_s}}{2\sqrt{3}}$$

In this case, $k_1 = k_2 = k$ due to symmetry about $\bar{\lambda}_s$.

Therefore,

$$\sigma_{\lambda_s} = \frac{k}{\sqrt{3}} \sigma_{\lambda_s}$$

or

$$k = \sqrt{3}$$

The density function of λ_s will not necessarily be symmetrical about $\bar{\lambda}_s$; in which case $k_1 \neq k_2$. Thus, define

$$S = \frac{k_2}{k_1} = \text{symmetry parameter.}$$

$$\lambda_{s_{max}} = \bar{\lambda}_s + k_1 \sigma_{\lambda_s} = \left(1 + \frac{k_1 \sigma_{\lambda_s}}{\bar{\lambda}_s}\right)\bar{\lambda}_s \tag{8}$$

$$\lambda_{s_{min}} = \bar{\lambda}_s - k_2 \sigma_{\lambda_s} = \left(1 - \frac{sk_1 \sigma_{\lambda_s}}{\bar{\lambda}_s}\right)\bar{\lambda}_s \tag{9}$$

Define

$$r = \frac{k_1 \sigma_{\lambda_s}}{\bar{\lambda}_s} \tag{10}$$

From equations (6), (8), (9), and (10):

$$X_2 - X_1 = \log\left(\frac{\lambda_{s_{max}}}{\lambda_{s_{min}}}\right) = \log\left[\frac{(1 + r)}{(1 - rs)}\right] \tag{11}$$

$$\frac{(1 + r)}{(1 - rs)} = 1 + \frac{r(1 + s)}{(1 - rs)}$$

Define

$$U = \frac{r(1 + s)}{(1 - rs)}$$

$$X_2 - X_1 = \log(1 + U) \tag{12}$$

$$\ln(1 + U)^* = 2\left[\frac{U}{(2 + U)} + \frac{1}{3}\left(\frac{U}{2 + U}\right)^3 + \ldots\right] \tag{13}$$

---

*Mathematical Tables, Ninth Edition, 1951, p. 281, Chemical Rubber Publishing Co.

where

$$(-1 < U < +\infty)$$

$$s = \frac{k_2}{k_1};\ 0 < s < +\infty$$

$$r = \frac{k_1 \sigma_{\lambda_s}}{\bar{\lambda}_s}$$

is always positive and will be less than 1 for the cases under study.

$$0 < r < 1$$

$$U = \frac{r + rs}{1 - rs}$$

Therefore, U will be within the desired range of $-1 < U < +\infty$.

Furthermore:

$$\ln (1 + U) \cong \frac{2U}{2 + U} \qquad \text{if } U \leq 3 \text{ or } rs \leq 0.6 \tag{14}$$

Therefore,

$$\ln (1 + U) \cong \frac{2 (r + rs)}{(2 + r - rs)} \tag{15}$$

$$\log_{10} (1 + U) = 0.434295 \ln (1 + U) \tag{16}$$

$$\alpha' = -\frac{1}{\log_{10} (1 + U)} \cong -\frac{1.15 (2 + r - rs)}{r (1 + s)} \tag{17}$$

or

$$\alpha' \cong -\left[\frac{2.30}{k_1 (1 + s)} \left(\frac{\bar{\lambda}_s}{\sigma_{\lambda_s}} \right) + \frac{1.15 (1 - s)}{(1 + s)} \right] \tag{18}$$

for

$$|\alpha'| \geq 1.9$$

For a symmetrical pdf, equation (18) reduces to:

$$\alpha' \cong - \frac{1.15}{k_1}\left(\frac{\bar{\lambda}_s}{\sigma_{\lambda_s}}\right) \tag{19}$$

where

$$k_1 = \frac{\lambda_{s_{max}} - \bar{\lambda}_s}{\sigma_{\lambda_s}}$$

Therefore,

$$\alpha' \cong - \frac{1.15}{\left(\frac{\lambda_{s_{max}}}{\bar{\lambda}_s} - 1\right)} \tag{20}$$

$$\alpha' \geq 1.9$$

Stress Factor Consideration

The following diagram shows the effects on $\bar{\lambda}_s$ and σ_{λ_s} of varying the stress factors. Assume that λ_1, can be influenced by vibrationlevel only, λ_2 can be influenced by vibration at a particular resonant frequency, and λ_3 can be influenced by temperature only. Inherently $\lambda_1 = 1$, $\lambda_2 = 2$, and $\lambda_3 = 3$ (in arbitrary units).

Initially

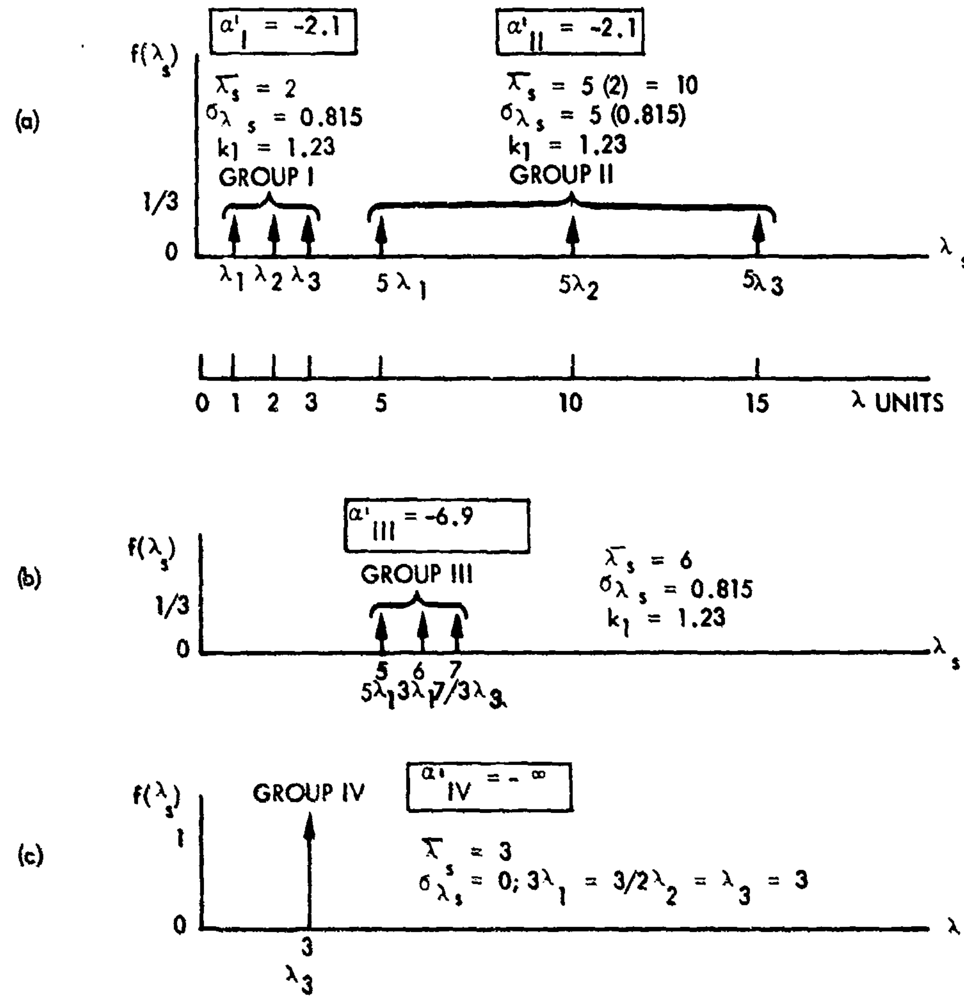
$$\bar{\lambda}_s = 2$$

and

$$\sigma_{\lambda_s} = \sqrt{\frac{2}{3}} = 0.815$$

If all λ's are increased by a factor of 5 as in (a), the new $\bar{\lambda}_s$ and σ_{λ_s} will be five times higher than initially. Equation 7 shows that α' is unaltered. Diagram parts (b) and (c) show the changes in α' by altering the λ's by the amounts shown.

Environmental stress factors cause the effective λ_{s_i} to be greater than the inherent λ_{s_i} by some factor, k_i, which is not linear in general. Increasing the temperature above room temperature by (1) increasing the ambient temperature or by (2) lowering cooling air rate, for example, on a transistor will result in a decrease in MTBF (i.e., an increase in its "inherent" λ). Increasing the level of input vibration of a structure or part near its resonant frequency causes an increase in λ according to the corresponding stress cycles to failure curve for fatigue-type failure mechanisms. Also, maintaining the vibration frequency at resonance for a long time by using a slow vibration sweep rate



compared to using a fast sweep rate causes λ to be larger for fatigue-type failure mechanisms. Changing the nature of vibration from sinusoidal to random causes a change in λ. Ways of estimating the various damage potentials of these widely differing environmental stresses is available in the literature and will not be discussed here.

There are other mechanisms that are sensitive to levels above some threshold. A loose solder ball, nut, or washer may relocate and cause a short circuit if its acceleration exceeds 1g. A bolt may become loose above a threshold amplitude.

There are still other failure mechanisms that are sensitive only to the combination of environments.

An antenna, secured by a tapered shaft with a captive end nut, can lose boresight as a result of combined temperature and vibration environment. There are cases (levels) where neither environment, individually, will cause the slippage. Many other examples could be cited. The main point is that the reliability engineer has many ways selectively to alter the λ's by synthesizing the desired reliability environmental test.

Insofar as the changes in the λ_S due to environment can be reflected in the underlying distribution of new, accelerated, higher $(\lambda_S)_{NEW}$, then the effects on α can be calculated/predicted with some rigor. But this problem has plagued reliability engineers for years without solution other than reasonable empirical approximation.

The diagram shows 3 hypothetical cases of the effects of environmental acceleration on λ_S, and the corresponding, but widely varying effect on α'. These distributions were contrived to show the dramatically different effect on α' that relatively mild changes to failure rate acceleration factors can have.

Diagram (a) shows a set of 3 systematic failure, λ_1, λ_2, λ_3, all accelerated equally by a factor of 5. They take on a new mean, λ, which is 5 times the old. They exhibit a new standard deviation about the new mean, $\sigma\lambda_S$, which is 5 times the old. But, the ratio $\bar{\lambda}/\sigma$, does not change, and therefore, α', is invariant in spite of dramatic environmental effects on the $\bar{\lambda}_S$.

In (b), we hypothesize that $\lambda 1$ could be increased (accelerated by environment) by a factor of 5, λ_2 by 3, λ_3 by 7/3. In this case the mean λ_S was increased by 6/2 = 3, but σ = .815 before and after, unchanged (deliberately). Because the ratio $\bar{\lambda}/\sigma$ is now considerably increased, α' also increases.

In (c), λ_1 and λ_2 are independently increased such that all $3\lambda_i$ are equal afterward. σ is now zero, and α' is infinite. This result implies that all 3 failure mechanisms are removed simultaneously and discontinuously.

E. RELIABILITY INVESTMENT ANALYSES FOR HIGH PERFORMANCE AIRCRAFT AVIONICS

1. INTRODUCTION

This subsection dimensions and analyzes elements of reliability costs, termed investments, and establishes models to evaluate their interrelationships, value, and impact on life cycle maintenance costs.* The subsection analysis is structured in the following sequence:

- Reliability Test Investment and Life Cycle Maintenance Cost (Model Derivation)
- Computer Program for Reliability Test Investment Analysis (LIFCO)
- RDT&E Reliability Investment Analysis and Life Cycle Cost Impact
- Production Program Reliability Investment Analysis
    - Parts Screening Cost Model
    - Product Screening Cost Model

*Life cycle costs as referred to and utilized herein have been simplified to include only the equipment recurring field maintenance costs/savings based on maintenance manhours and replacement material excluding all other logistics support cost factors.

2. SUMMARY

- Reliability Test Investment and Life Cycle Maintenance Cost

  A mathematical model is derived relating the cost factor variables associated with reliability growth testing with selected factors identified as impacting equipment life cycle maintenance costs. Using the variables selected, the model developed permits determination of optimum reliability test investment within the context and limits of stated simplifying assumptions.

- Computer Program for Reliability Test Investment Analysis

  The above model has been generalized and refined into a computer program capable of evaluating optimum reliability test investment, dimensioning MTBF goals, estimating test schedules and testing the sensitivity of reliability factors for a variety of given conditions.

- RDT&E Reliability Investment Analysis and Life Cycle Cost Impact

  The APQ-113 RDT&E reliability program elements are dimensioned in terms of contract value to size the investment required to achieve demanding reliability requirements. The attendant cost leverage of reliability investment to maintenance savings is also presented.

- Production Program Reliability Investment Analysis

  The value of parts and product screening are assessed based on savings attributed to the relationships of costs of failures in the factory versus the field and the associated failure rates experienced for the APQ-113 program.

3. RELIABILITY TEST INVESTMENT AND LIFE CYCLE MAINTENANCE COST

a. Introduction

Reliability tests cost money! Maintenance of unreliable equipment over its life-cycle costs a great deal MORE money. The question arises: "When does the incremental cost of MTBF improvement through reliability growth testing equal the incremental saving in maintenance costs over equipment life-cycle by doing so?" This question is analyzed in the following model derivation which permits establishing guidelines for cost/resource management.

b. Derivation Model

The model is derived in terms of MTBF; however, for convenience the resulting expressions are also shown in terms of failure rate (λ).

As described in the Alpha Derivation subsection of this report, the reliability growth of an equipment during RET can be mathematically expressed by the following equation:

$$M = M_i \left(\frac{t}{t_i}\right)^{\alpha} \tag{21}$$

where

M = MTBF measured after t hours of testing which is assumed to remain constant thereafter

M_i = MTBF initially, at time t_i

t = Accumulated test time

α = Slope of reliability (i.e., MTBF growth curve)

To evaluate M_i use the "10% Rule" of RPM, i.e., when t_i = 100 hours, $M = M_p/10$, where M_p is the predicted MTBF.

Then

$$M = \frac{M_p}{10}\left(\frac{t}{100}\right)^{\alpha} \tag{22}$$

When α = 1/2 (a value demonstrated in several test programs)

$$M = \frac{M_p}{100}\, t^{1/2} \tag{23}$$

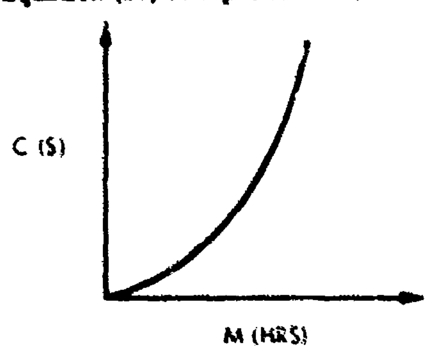
and solving for t

$$t = \frac{10^4 M^2}{M_p^{\ 2}} \tag{24}$$

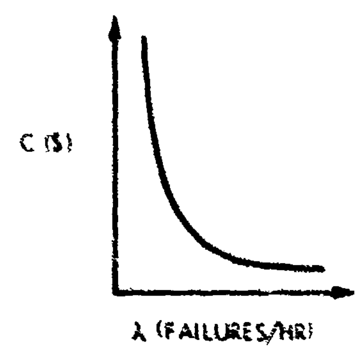
Let k' be the cost of performing reliability tests in \$/hour, and C be the total test cost in dollars.

$$C = k't = \frac{k'10^4 M^2}{M_p^{\ 2}} \quad \text{or} \quad \frac{k'10^4 \lambda_p^{\ 2}}{\lambda^2} \quad \text{where } M = \frac{1}{\lambda} \text{ and } M_p = \frac{1}{\lambda_p} \tag{25}$$

Equation (25) is a parabola C/M or a more complicated function C(λ).



OR



It follows that the incremental change in cost, dC, caused by a change in MTBF, dM, is:

$$\frac{dC}{dM} = \frac{2k'\,10^4}{M^2_{\;p}}\,M \quad \text{or} \quad \frac{dC}{d\lambda} = -\frac{2k'10^4\lambda_p^{\;2}}{\lambda^3} \tag{26}$$

In a life-cycle of T hours of operation of an equipment, 10T/M maintenance actions will occur. *

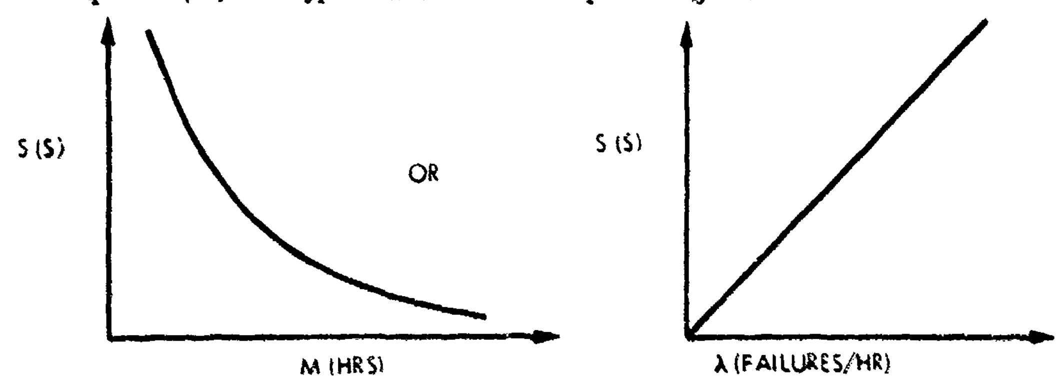
Furthermore, a reasonable average cost of a basic maintenance action is $220**. Then the life-cycle cost of maintenance in dollars is:

$$S = (220)\,(10)\,\frac{T}{M} = 2200\,\frac{T}{M} \quad \text{or } 2200\,\lambda T \tag{27}$$

where

S = Total maintenance related life-cycle cost, excluding items identified in the footnote.

Equation (27) is a hyperbola in M or a simple straight line in λ.



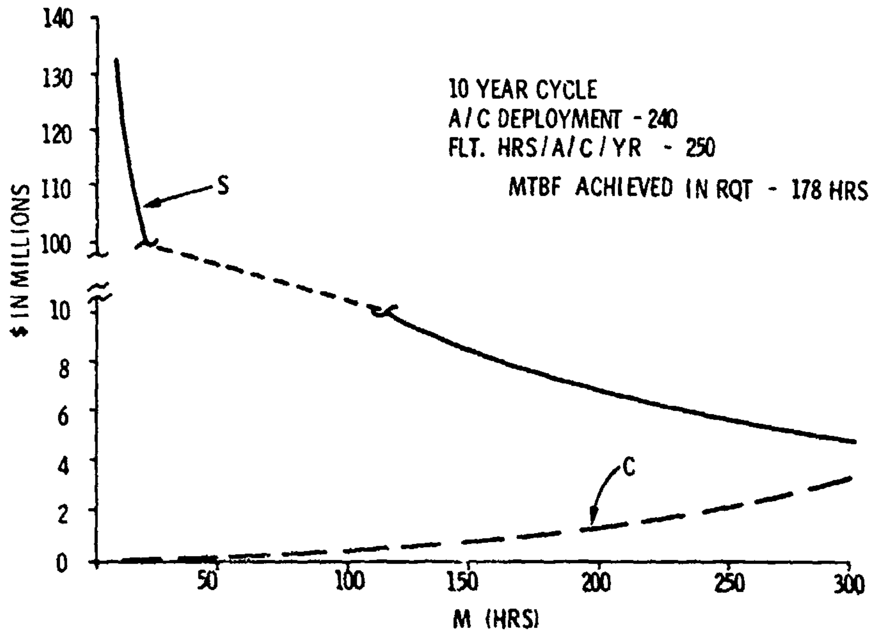
Model Simplification Assumptions: (Precautions for model use are provided on page 61.)

- Operational maintenance tasks are proportional to test MTBF.
- Field MTBF is a constant related to test MTBF - this also assumes that field stresses are constant.
- The average cost of a maintenance task is $220. It is recognized that individual tasks vary, based on difficulty.

Equations (25) and (27) are plotted below for typical values of the variables, related to GE/AESD experience with actual Air Force programs.

*The ratio of factory demonstrated MTBF to the 66-1 reported field M rate is approximately 10:1 (See Field Performance Analysis)

**This cost is only maintenance man-hours and replacement material excluding all other logistics support cost factors.



The rate of change of S with respect to M is

$$\frac{dS}{dM} = -\frac{2200\,T}{M^2} \quad \text{or} \quad \frac{dS}{d\lambda} = 2200T \qquad (28)$$

with the minus sign denoting only that S decreased as M increases.

Equation (28) gives the incremental savings, dS, due to increasing M by an amount dM.

Upon equating (26) to (28) and ignoring the minus sign:

$$\frac{2k'\,10^4}{M_p^2}\,M = \frac{2200\,T}{M^2}\,.$$

$$\text{and } M = \left(\frac{1.1\,TM_p^2}{10k'}\right)^{1/3} \quad \text{or} \quad \lambda = \left(\frac{10\,k'}{1.1\,T M_p^2}\right)^{1/3} \qquad (29)$$

Equation (29) determines that value of M where the slope of curve C equals the slope of curve S. Also, equation (29) determines that value of M where the cost of reliability improvement through test equals the life-cycle savings, when:

1) The 10% Rule applies (RPM).

2) $\alpha = 1/2$

3) Test cost is assumed to be proportional only to test time.

4) The number of maintenance actions in field is 10 times the factory-demonstrated MTBF.

5) The cost of each maintenance action is $220.

The above model equation has been generalized, making it independent of the above five restrictions and refined to include the following additional variables in a computer program:

1) Nonrecurring cost of test equipment

2) Nonrecurring cost of equipment under test (recoverable with reasonable refurbishment)

3) Recurring cost of Corrective Action relating to test failures/problems

4) Calendar time to achieve the indicated MTBF

This computer program, called LIFCO, allows one to optimize resources against a variety of rationales. Examples of the model capability and application are:

1) Determining the optimum reliability test investment based on maintenance life-cycle costs for a given program force structure.

2) Dimensioning equipment MTBF goals based on optimization of reliability test investment with projected maintenance life cycle costs.

3) Estimating the test program schedule time required to achieve the specified MTBF based on the resources allocated.

4) Determining the impact on reliability test investment, life-cycle cost or MTBF achievement by changing any of the program variables.

IMPORTANT PRECAUTIONS TO BE OBSERVED:

Some very practical considerations must be applied to effectively use this theoretical model:

1) The equipment MTBF that can be achieved through R growth testing is limited to that predictable within the test stresses applied, using realistic failure rates based on Mil-Handbook-217, and considering contractor and Air Force experience (refer to RPM Criteria and Constraints, page 27).

2) Recognition that some design changes introduced to increase reliability (MTBF) could result in higher equipment maintenance costs. The computer program permits selection of any average cost of a maintenance action.

3) Many factors unrelated to equipment reliability (MTBF) impact the total cost of field maintenance and need to be excluded when analyzing the worth of reliability investment in terms of field maintenance savings. Typical of other factors governing maintenance costs are: equipment utilization, personnel skill and experience, base manning levels, maintenance policy, and spares and support equipment availability.

4) Only the number of field maintenance actions resulting from equipment failure directly relatable to equipment reliability should be used in projecting life cycle maintenance costs/savings. In the computer program provided, the factor (MAF) permits conversion of test MTBF (M_a) to any desired value of projected field MTBMA.

4. COMPUTER PROGRAM FOR RELIABILITY TEST INVESTMENT ANALYSIS

PROGRAM   LIFCO

LANGUAGE   BASIC

MACHINE   GENERAL ELECTRIC MARK II TIME SHARE

DESCRIPTION

This computer program, using the identified variables, relates reliability test investment cost to fielded equipment maintenance costs, based on test achieved MTBF.

TEST TIME (Hours)

$$t_a = t_i \left[\frac{M_a}{M_i} \right]^{1/\alpha}$$

where

t_i = Initial accumulative hours (empirically established at $\simeq 100$ hours)

M_i = Initially observed MTBF (at t_i)

M_a = Test achieved MTBF (the program calculates M_a as a percent of M_p)

M_p = Predicted MTBF (See Note)

α = Reliability growth slope (practically constrained to < 0.6)

NOTE: If per RPM, the predicted MTBF M_p = 125% of the required MTBF, then cost tradeoff analyses based on the computer model should be made at the point $M_a = 0.8\ M_p$.

TEST COSTS (Dollars)

$$C_t = (TC)(t_a) + CAC(t_a) + TA + NRCTE$$

where

TC = Test Cost in \$/hr of test

CAC = Corrective Action Cost in \$/hr of test

TA = Test Asset Cost (value of prime equipment consumed in test or refurbishment cost when not consumed)

NRCTE = Nonrecurring test equipment costs

SERVICE COSTS (Dollars)

$$C_s = \frac{(C_m)(MAF)(T)}{M_a}$$

where

C_m = Cost per maintenance action (\$)

MAF = Maintenance acts/failure (this factor is used to convert test achieved MTBF (t_a) to projected field MTBMA, i.e., MAF = M_a/Field MTBMA)

T = Equipment field life cycle in hours

T = (N) (P) (F)

where

N = Number of aircraft programmed or deployed

P = Field life cycle in years

F = Flight hrs/aircraft/year

CALENDAR TIME (Months)

$$Y = \frac{t_a}{X}$$

where

X = Hours per month of effective test time

$$X = (X_1)(X_2)(S)$$

where

X_1 = Available test hours per month

X_2 = Efficiency in terms of decimal ratio of time utilized versus time available

E = Number of equipments concurrently on test

The program permits a variety of input/output options and routines by varying a single input over a wide range of values to determine the model's sensitivity to that variable or to establish a family of cost and cost ratio relationships between selected program variables.

INPUT (Attachment I - Typical Input Statement)

A selection of (1) a base case resident in the program or (2) individual inputs of 18 variables. Description of the variables is as shown on preceding pages.

Symbol	Description of Variable	Computer Program Variable
M_p	Predicted MTBF in hours	A(1)
C_m	Cost per Field Maintenance Action in $	A(2)
TC	Test Cost in $/hr	A(3)
T	Life Cycle in hours	A(4)
N	Number of Aircraft Programmed or Deployed	A(6)
P	Equipment Field Life Cycle in years	A(7)
F	Flight Hours/Aircraft/Yr	A(8)
MAF	Maintenance Acts/Failure	A(5)
α	Alpha as a decimal	A(9)
t_i	Initial Accumulative Test Hours	A(10)
M_I	Initial MTBF in hours	A(17)
CAC	Corrective Action Costs in $/hr of Test	A(13)
TA	Test Assets in $	A(11)
NRCTE	Nonrecurring Test Equipment Costs in $	A(12)
X	Effective Test Hours per Month	A(18)

Symbol	Description of Variable	Computer Program Variable
X_1	Available Test Hours per Month	A(14)
X_2	Test Hour Efficiency in %	A(15)
E	Number of Equipments on Test	A(16)

OUTPUT

The program output is selectable in terms of a detailed printout by 10% increments of MTBF achieved (M_a) with a minimum total cost program calculation or only the 100% MTBF achieved and minimum cost printout. The output is also selectable in terms of dollars of test and service costs (Attachment II) or ratios of test and service cost per hour of MTBF achieved (Attachment III).

ATTACHMENT I

- LIFCO -

TYPICAL INPUT STATEMENT

```
DO YOU WANT TO CALC AVAIL TEST HRS...YES-1..NO-2
? 1
AVAIL HRS PER MO
? 600
TEST EFFECIENCY IN %
? 33.33
NO.OF EQUIPMENTS
? 2
MTBF PREDICTED IN HRS
? 178
COST PER MAINT ACT IN $
? 220
TEST COST IN $/HR
? 75
LIFE CYCLE IN HRS
DO YOU WISH TO CALCULATE...YES-1..NO-2
? 1
NO. OF A/C
? 1000
NO. OF YRS LCC FIELD
? 10
FLT HRS/AC/YR
? 250
MAINT ACTS/FAILURE
? 2
ALPHA AS A DECIMAL
DO YOU WISH TO CALCULATE ALPHA..YES-1..NO-2
? 2
INPUT YOUR OWN VALUE
? .5
ACCUM HRS-INITIAL
? 100
INITIAL MTBF
? 17.8
CORRECTIVE ACTION $/HR
AS A FUNCTION OF TEST COST AND ALPHA-1 OR FIXED-2
? 2
INPUT FIXED VALUE
? 45
TEST ASSETS $
? 0
NRC TE $
? 220000

PRINTOUT SELECTION...COMPLETE-1...OR MIN$-2
? 1
CHARGES-1......OR RATIOS-2
? 1
----------------------------------------------------------
```

ATTACHMENT II

- LIFCO -

MTBF ATTAINED BY INCREMENTS OF PREDICTED

```
P-MTBF(1):       178 I-MTBF(17): 17.8 I-HOURS(10): 100

ALPHA(9):  0.5
FIX E'NESS FACTOR(19): 0 FIX E'VITY FACTOR(20): 0
LIFE CYCLE(4):  2500000 NO.A/C(6): 1000 NO.YRS(7): 10 FH/AC/YR(8): 250

MAINT ACTS/FLR(5): 2 $/MA(2):  220 TC-$/HR(3): 75 CAC-$/HR(13): 45

TEST ASSETS-$(11):   0 NRC TE$(12): 220000

AVAIL TEST HRS-(18): 399.96
HRS/MO AVE(14):  600 TEST EFF %(15): 33.33 NO.OF EQ'S(16): 2
```

MTBF ATTAINED %	HRS	MOS	TEST CHARGES $	SERV CHARGES $	TOTAL $	RATIO S$/T$
10.	17.8	0.3	232000	61797753	62029753	266.4
20.	35.6	1	268000	3.08989E+7	3.11669E+7	115.3
30.	53.4	2.3	328000	20599251	20927251	62.8
40.	71.2	4	412000.	1.54494E+7	1.58614E+7	37.5
50.	89.	6.3	520000.	1.23596E+7	1.28796E+7	23.8
60.	106.8	9	652000.	1.02996E+7	1.09516E+7	15.8
70.	124.6	12.3	808000.	8.82825E+6	9.63625E+6	10.9
80.	142.4	16	988000.	7.72472E+6	8.71272E+6	7.8
90.	160.2	20.3	1.192E+6	6866417	8058417	5.8
100.	178.	25	1.42E+6	6.17978E+6	7.59978E+6	4.4
110.	195.8	30.3	1.672E+6	5.61798E+6	7.28998E+6	3.4

ATTACHMENT III

- LIFCO -

VARIATIONS OF LIFE CYCLE COSTS OVER A FORCE STRUCTURE RANGE

10,000 HRS → 2,500,000

MTBF ATTAINED %	HRS	MOS	TEST CHARGES $	SERV CHARGES $	TOTAL $	RATIO S$/T$
80	142.4	16	988000	7.41573E+6	8.40373E+6	7.5
VARIABLE NO.- 4 2400000						
10	17.8	0.3	232000	59325843	59557843	255.7
80	142.4	16	988000	6.17978E+6	7.16778E+6	6.3
VARIABLE NO.- 4 2000000						
10	17.8	0.3	232000	4.94382E+7	4.96702E+7	213.1
80	142.4	16	988000	4.94382E+6	5.93182E+6	5
VARIABLE NO.- 4 1600000						
10	17.8	0.3	232000	39550562	39782562	170.5
80	142.4	16	988000	3.08989E+6	4.07789E+6	3.1
VARIABLE NO.- 4 1000000						
10	17.8	0.3	232000	2.47191E+7	2.49511E+7	106.5
80	142.4	16	988000	1.85393E+6	2.84193E+6	1.9
VARIABLE NO.- 4 600000						
10	17.8	0.3	232000	1.48315E+7	1.50635E+7	63.9

CASE CHNG-1,CHANGES-2,MULT CHNG-3,PRINT VALUES-4,END-5
?

ATTACHMENT III (Continued)

```
-----------------------------------------------------------------
 80    142.4  16    988000     617978.        1.60598E+6    0.6
VARIABLE NO.- 4  200000
 10    17.8  0.3    232000     4.94382E+6     5.17582E+6    21.3
-----------------------------------------------------------------
 80    142.4  16    988000     247191.        1.23519E+6    0.3
VARIABLE NO.- 4  80000
 10    17.8  0.3    232000     1.97753E+6     2.20953E+6    8.5
-----------------------------------------------------------------
 80    142.4  16    988000     123596.        1.1116E+6     0.1
VARIABLE NO.- 4  40000
 10    17.8  0.3    232000     988764.        1.22076E+6    4.3
-----------------------------------------------------------------
 80    142.4  16    988000     30898.9        1.0189E+6     0
VARIABLE NO.- 4  10000
 10    17.8  0.3    232000     247191.        479191.       1.1
-----------------------------------------------------------------
CASE CHNG-1,CHANGES-2,MULT CHNG-3,PRINT VALUES-4,END-5
?
```

5. RDT&E RELIABILITY INVESTMENT ANALYSIS AND LIFE CYCLE COST IMPACT

a. Objectives

The primary objectives of this subsection are to relate the reliability investment costs required during the RDT&E phase of tne APQ-113 development program to the total RDT&E program costs. Having established these, the relationships between investment and field maintenance savings are portrayed and quantified.

b. Summary

On a new, high performance aircraft avionics program, where the reliability requirements are demanding, an investment approximately equal to 20% of the RDT&E nonrecurring program costs is required for reliability disciplines and practices. Reliability evaluation testing (RET) alone accounts for 55% of this investment; however, savings in field maintenance in the order of 50:1 are projectable for just this portion of the investment, depending on the size of the programmed force structure and achieved equipment MTBF.

c. Investment Analysis

To structure and dimension the reliability cost model, the APQ-113 program elements and costs were analyzed and related. In order to afford an orderly and generally applicable model, only the nonrecurring RDT&E costs were selected, while costs associated with prototype fabrication - labor, material, etc. - were excluded because the quantity of equipments normally varies from program to program.

It was deemed appropriate to subdivide the costs into three basic reliability RDT&E categories:

1) MIL-STD-785 Pre-release Reliability Practices. Provides for reliability involvement and considerations throughout all aspects of design, development, and production and assures that the specified reliability performance requirements can be met. These practices generally encompass the following areas of reliability control:

- Parts Reliability - Preferred Parts - Evaluation/Qualification Tests
- Reliability Apportionment
- Reliability Predictions
- Design Techniques - derating, stress analysis, redundancy
- Worst Case analysis
- Failure Mode and Effects Analysis
- Reliability of Critical Items
- Design Reviews

- Manufacturing and Test Reliability
- Evaluation Tests

2) RPM Growth Program. Includes reliability evaluation testing, with associated failure analysis and corrective action. This program must be structured in consonance with the optimization routines presented in other sections to maintain the relative cost relationships.

3) Reliability Qualification Test. Cost associated with performing the final demonstration test of achieved reliability.

NOTE: It is paramount to recognize that reliability growth to the predicted level is not achievable if the reliability disciplines identified in MIL-STD-785 are not implemented. Similarly, total reliability achievement can only be obtained through a properly structured reliability evaluation test program.

The APQ-113 RDT&E cost structure analysis has indicated that an investment in reliability disciplines approximately equal to 20% of total nonrecurring RDT&E cost is necessary to achieve reliability compliance prior to production. It is important to recognize that this 20% ratio is applicable to a 100% new design release. Designs with different degrees of design inheritance may require other ratios of reliability investment to RDT&E program costs. It is probable that the relative percentages will increase.

The 20% reliability cost of RDT&E programs is composed of a set of elements within the three primary ones, discussed earlier, dividing the costs as follows:

- 5% for prerequisite MIL-STD-785 Pre-release Practices
- 4% for Reliability Qualification Tests
- 11% related to Reliability Evaluation Tests

The evaluation tests are further segregated into two principal categories:

- Cost of Test
- Cost of Failure Corrective Action

Test costs accounting for 6% of RDT&E costs include the cost of:

- Test Equipment
- Test Facilities
- Test Labor
- Repair Costs
- Test Monitoring and Planning

The 5%, costs attributed to corrective action, consists of:

- Engineering Design Evaluations
- Reliability Parts Failure Analysis - down to failure mechanisms
- Quality Assurance - workmanship failure assessments
- Cost of Corrective Actions - part vendors, engineering redesign, manufacturing changes

The reliability cost model derived from the APQ-113 is depicted in Figure 17. It has been found that costs do not relate to achieved MTBF on a straight line basis for several reasons. principally:

1) Systematic failures detection rate decreases per unit of test time.

2) Failures detected in the later test phases are normally complex requiring more analysis and more in-depth corrective action than earlier failures.

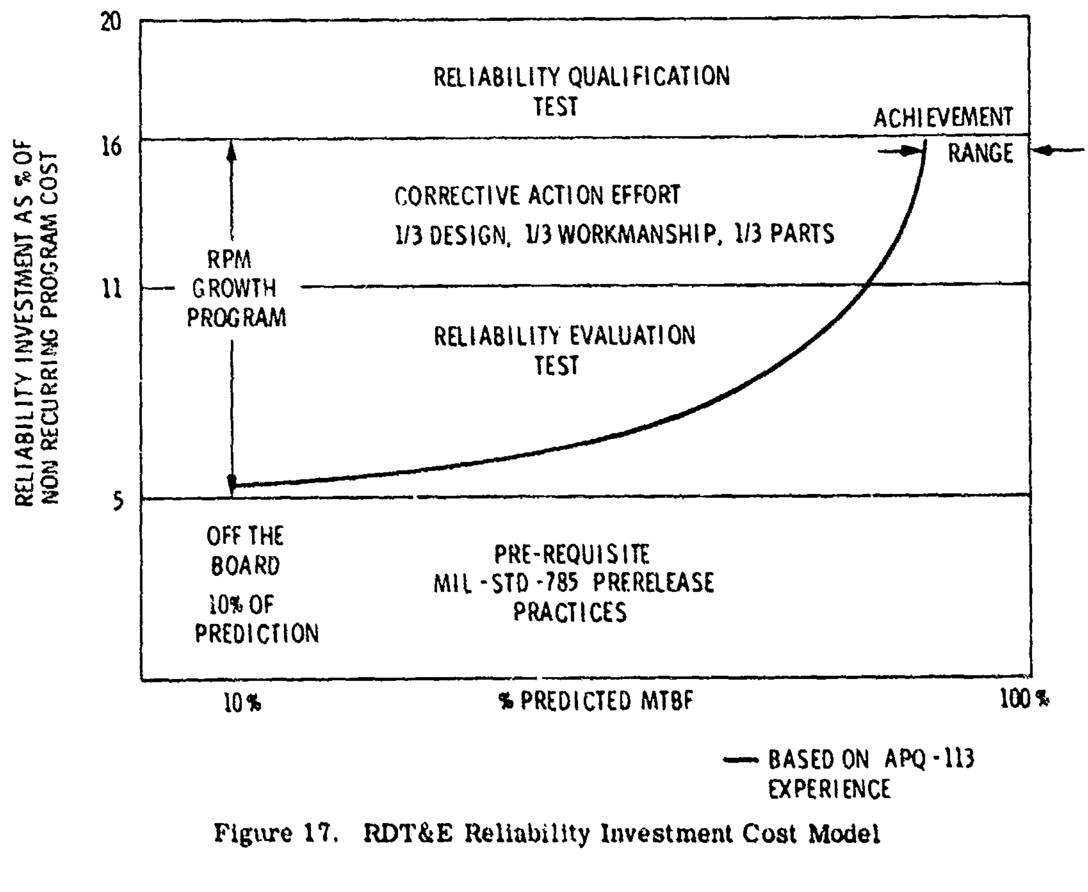


Figure 17. RDT&E Reliability Investment Cost Model

The model in Figure 17 illustrates several of the relationships discussed in this study:

- MIL-STD-785 is a prerequisite to reliability evaluation testing.
- The 10% initial performance even after all the pre-release disciplines have been implemented.
- The 1/3, 1/3, 1/3 failure distribution constraining the initial performance.
- The separation of the RQT and RET with the RQT being the customer proof test and the RET being the contractor growth testing.
- The "achievement range" indicates the variability in the dollars to MTBF relationship.

d. Life Cycle Cost Impact - High Performance Aircraft Avionics

Reliability growth programs are not cheap - but can result in significant savings to the end user. This section evluates the leverage which an investment in reliability growth testing has upon life cycle maintenance costs.

Application of the cost model through the use of the LIFCO* computer program has provided a variety of analyses. The two most applicable are reflected in Figure 18 and Figure 19 based on data inputs shown on page 66, representative of the APQ-113 example.

In Figure 18 it can be seen that a minimum savings leverage for this example is in excess of 50:1, i.e., ratio of dollars invested in the reliability growth test to the savings projected considering maintenance costs, at $220 per maintenance action. The ratio is obtained by comparing the net cost of maintenance (61M - 7.7M) = 53.3M vs 1M investment = 53:1.

This savings is based on the difference between growth test achieved reliability and the off-the-board initial test reliability at 10% of predicted. Typical deployment periods, flight hours, and aircraft inventory were used and are identified in the sample computer printout.

Readily seen are the rapid recovery of test investment cost and the significant savings in maintenance cost assuming that the MTBF improvement realized persists in field performance. Not reflected in the maintenance cost are the additional logistics costs associated with low reliability, e.g., spares, AGE, mission effectiveness, maintenance facilities, aircraft down town, training, changes, all of which would serve to enhance the value of the reliability test investment.

Figure 19 portrays the effects of a given MTBF on field maintenance cost and related reliability test investment costs, stressing the importance of specifying the optimum achievable MTBF requirement and assuring compliant reliability performance. Figure 19 is based on the same quantities as the inputs for Figure 18 and the total savings are based on costs of $220 per maintenance action.

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*LIFCO - An acronym for the GE program developed for this study.

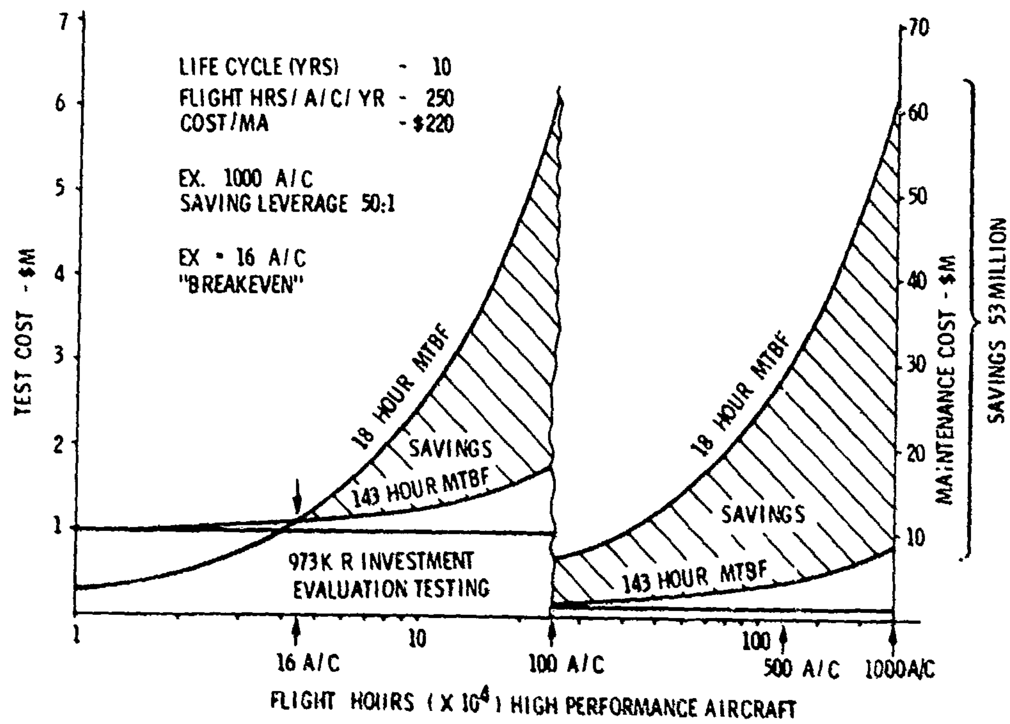

Figure 18. Maintenance Cost vs Flight Hours

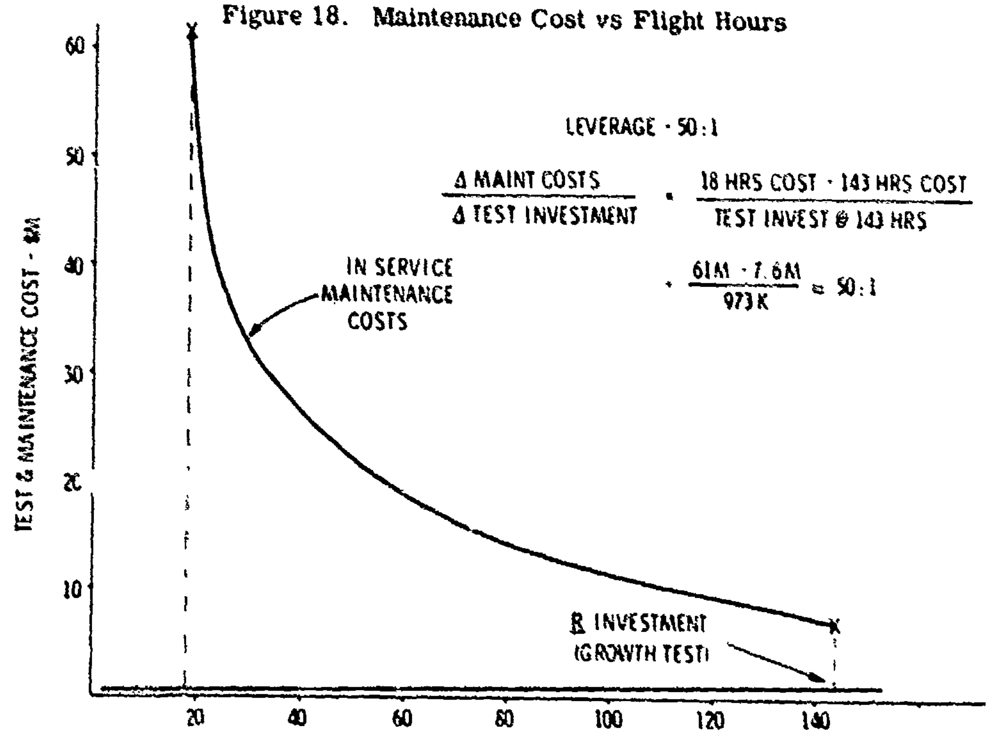

Figure 19. Reliability Growth Test Investment versus Life Cycle Cost

6. PRODUCTION PROGRAM RELIABILITY INVESTMENT ANALYSIS

a. Introduction

Equipment reliability performance and achievement is largely determined by the decisions and investments made during the RDT&E program phase. However, to complement and sustain the RDT&E program investments and achievement requires continued disciplines throughout the production program.

Two of the significant production program disciplines discussed in this report as essential to meeting the APQ-113 reliability requirement were:

1) Parts Environmental Screening

2) Product Environmental Screening

The objective of this part of the report is to dimension the cost effectiveness of each of these disciplines as applied on the APQ-113 program.

NOTE: Cost of failure values used herein were not derived as part of this study. The numbers were obtained from factory and field sources and are judged to be reasonable based on being best estimates of the user's experience. Expressions derived utilizing these numbers have been presented in general terms in order that they may be evaluated over a range of input values.

b. Parts Screening and Burn-In

INTRODUCTION

The APQ-113 program utilized high reliability parts based on having a contractually enforced demanding equipment MTBF requirement. At the time of the decision, cost effectiveness was a secondary consideration to meeting the contract requirement. This section evaluates the merits of parts screening based on the improved part failure rates experienced, and cost of part failures, compared to the additional average cost of a screened part. One objective of this analysis is to demonstrate that it is cost effective to identify and remove part failures at the point of lowest cost per failure, which is the part manufacturer. Another objective is to show that the higher material costs of screened parts is largely offset by reduced equipment manufacturing costs.

It is recognized that many factors contribute to the cost of a screened part including part type, lot quantity, and type of screening required. The APQ-113 parts screening cost analysis is based on the practices described in Table XIV in Section III and the cost of parts screening at an early stage of its development.

CONCLUSIONS

This study has concluded that use of high reliability parts on the APQ-113, necessary to meet the contractually specified MTBF, also had positive economic payoffs over and above the higher material costs initially incurred by the radar manufacturer.

COST ANALYSIS

The cost effectiveness (E) per radar of using high reliability parts versus standard parts is expressed in the following equations, which relate the costs of implementing high reliability parts into equipment, to the cost savings achieved in the manufacturing cycle, at platform and in the field. These savings are based on the experienced failure rate differentials between high reliability and standard parts at these levels and their relative costs of failure:

$$E = \frac{Q\,[\overbrace{C_1(P_1-P_2) + C_2(P_3-P_4) + AC_3(P_5-P_6)}^{\text{Factory}} + \overbrace{C_4(P_7-P_8)}^{\text{Platform}} + \overbrace{C_5(P_9-P_{10})}^{\text{Field}}]}{C \times Q} \tag{30}$$

and

$$\text{Savings per equipment: } S = Q\,C_1(P_1 - P_2) \ldots - C \times Q \tag{31}$$

where

E = Cost effectiveness of high reliability parts per equipment - (if $E > 1$, it is effective; if $E < 1$, it is not)

			APQ-113 Experience
C	=	Average additional cost of a high reliability part over a standard part	\$1.00
Q	=	Quantity of parts per equipment	10,700
P_1	=	% failures - standard parts* - at Incoming Test	3%
P_3	=	% failures - standard parts* - at In-Process Test	.4%
P_5	=	% failures - standard parts* - at RAT	.02%
P_7	=	% failures - standard parts* - at Platform	.03%
P_9	=	% failures - standard parts* - in Field (1 year)	.18%
P_2	=	% failures - high reliability parts - at Incoming Test	.6%
P_4	=	% failures - high reliability parts - at In-Process Test	.08%
P_6	=	% failures - high reliability parts - at RAT	.003%
P_8	=	% failures - high reliability parts - at Platform	.01%

*The values used for standard parts in the APQ-113 example were estimated based on GE experience on other programs.

P_{10}	=	% failures - high reliability parts - in Field (1 year)	.06%
A	=	% of systems presented to RAT	30%
C_1	=	Avg. cost of failure in \$ at Incoming Test (excl. Mat'l)	\$16
C_2	=	Avg. cost of failure in \$ in-process test	\$150
C_3	=	Avg. cost of failure in \$ at RAT	\$300
C_4	=	Avg. cost of failure in \$ at Platform	\$2500*
C_5	=	Avg. cost of maintenance action in \$ in Field	\$220

The above equations can be generally applied to any program with applicable or projected costs and percentages. The average failure percentages and costs for the APQ-113 are reflected adjacent to each factor.

Note that the field contribution to the savings is limited to one year of projected failures. This is because the percentage of part failures was taken from one year's APQ-113 field experience and the fallacy of projecting forward at this rate.

The "E" - effectiveness - of high reliability parts for the APQ-113 is therefore calculated as follows:

$$E = \frac{10,700 [\$16 (3\%-0.6\%) + \$150 (0.4\%-0.08\%) + 30\% \times \$300 (.02\%-.003\%)]}{\$1.00 \times 10,700}$$

$$+ \frac{10,700 \ \$2500 (.03\%-.01\%)}{\$1.00 \times 10,700} + \frac{10,700 \ \$220 (.18\%-.06\%)}{\$1.00 \times 10,700}$$

$$E = 1.65$$

Therefore, E being > 1, the worth of high reliability parts is positive, and was effective.

In the example provided, the distribution of savings occurs as follows:

$$E = \frac{\Delta \text{Savings/Part}}{\Delta \text{Cost/Part}} = \frac{\overset{\text{Factory}}{.88} + \overset{\text{Platform}}{.50} + \overset{\text{Field}}{.27}}{1.00} = \frac{1.65}{1.00}$$

This shows that the investment in high reliability parts is not fully recovered in the factory, during equipment manufacture, resulting in this case in a net 12% higher recurring equipment material cost amounting to \$1300 per radar. This would amount to less than

*Based on a parts failure distribution of two part failures during ground installation and checkout for each part failure during flight, at platform level.

one percent of the procurement cost of a radar of this type to implement ≈ 100 percent screened material. Even if higher equipment procurement costs are indicated, the decision to use high reliability parts is cost effective based on the total savings available when including those projected at platform and field levels.

Calculating the achieved overall savings per radar by substituting APQ-113 values into equation (31):

$$S = \$17,700 - \$10,700 = \$7000 \text{ savings per radar.}$$

Projecting this savings across the entire APQ-113 radar program for the 359 equipments delivered amounts to a total savings of $2.5M. By further projecting this across the entire APQ-113/114/144 quantities, by utilizing the APQ-113 costs and percentages, a net savings of 560 x $7000 = $3.9M can be projected.

c. Value of Product Environmental Screening

APQ-113 program LRU burn-in proved an effective test screen and failure precipitator as discussed in the failure distribution part of the Reliability Production Program Analysis section. In fact, the equipment's MTBF requirement would not have been achieved nor sustained without it.

Calculating the relative worth in dollars of performing product environmental screening at factory test, as opposed to the costs associated with not performing the test presumes that potential failures not found at factory test will occur in the field necessitating correction at a higher cost per failure. The analysis presented is based on the product screening described in Section III, pages 123 through 126.

In dimensioning the cost tradeoffs, the following elements warrant evaluation:

- I Investment Cost: Nonrecurring facilities, Test Equipment, Test Engineering and Planning
- T Burn-in test costs per equipment processed: Recurring costs associated with performing the test
- C Factory cost of a burn-in failure: Cost of troubleshooting, repairing and reprocessing
- C_1 Platform cost of a failure
- C_2 Cost of a platform failure under ground level checkout ambient conditions
- C_3 Cost of a platform failure under aircraft self flight environmental conditions
- Q Quantity of radars processed
- F_1 Factory burn-in failures: Failures per radar
- F_2 Platform failures: Failures per radar attributed just to the result of not having performed factory product screening

P Percent (decimal) of factory burn-in failures that would have escaped and occurred in the field at platform level as a result of not having performed factory burn-in

The above elements may be related in the following general expression which is structured assuming that screening is economically worth doing if the total cost of finding the failures in the factory is less than the cost of finding the failures at the field platform level.

$$\text{Factory Cost} < \text{Field Platform Cost} \quad \text{or} \quad I + Q(T + F_1C) < QF_2C_1$$

Note that the actual contribution of field failures beyond the platform level has been ignored since the platform level, like factory burn-in, provides the initial equipment environmental exposure. Also omitted from this equation is the cost of development and implementation of technical corrective action which is an independent analysis based on its contribution to reliability growth and the resulting effect of reducing both factory and field failure levels.

To estimate the tradeoffs in cost effectiveness without knowing F_2, the percent of the factory burn-in failures that would escape and fail, (P), times the factory failure rate (F_1), or PF_1, may be substituted for F_2. This permits solving the equation for P or examining the tradeoffs available based on varying assumed values of P.

Based on the cost per failure differences existing at platform in-process and flight test levels, the F_2 platform failures are broken into two primary components expressed as:

$$F_2 = F_A + F_E$$

where

F_A = Platform failures occurring at ground level check-out ambient conditions

F_E = Platform failures occurring under flight environmental conditions

The general expression can now be restated as follows:

$$I + Q(T + F_1C) < QP(F_AC_2 + F_EC_3)$$

Illustration, based on APQ-113/114/144 data:

I = \$500K

Q = 560 radars

T = \$2.5K/radar

F_1 = 5 failures/radar (Ref. Figure 47 - note this number ranged as high as 16 failures/radar when burn-in was first initiated and could be used as representing the worst case of not instituting burn-in)

$C = \$150/\text{failure (avg)}$

$C_2 = \$1000/\text{failure (avg)}$

$C_3 = \$5000/\text{failure (avg)}$

Assuming

$$F_1 = (F_A + F_E)$$

then for this example it is estimated that

$$F_A = 2 \text{ and } F_E = 3$$

based on factory experience where environmental testing precipitates 50% more failures than ambient test. This apportionment was also observed in the distribution of the APQ-120 platform failures.

Setting the factory costs equal to the field costs and solving the equation for P yields:

$$P = \frac{232 \times 10^4}{952 \times 10^4} = 0.24$$

This result means that under these conditions, the product environmental screening investment would have been completely amortized if only 24 percent of the factory burn-in precipitated failures had escaped to fail at the field platform level. Evidence that more than 24 percent of the factory burn-in failures would have occurred at platform level is provided in the study data (Reference Figure 53) where it is shown that 40 to 80 percent of the LRUs tested failed burn-in with approximately 40 to 50 percent of the failures occurring during the first temperature cycle.

Using the general expression developed and the dimensions of the APQ-113 example indicates a potential 4:1 cost leverage advantage to performing factory product environmental screening, assuming all of the burn-in failures escaped and failed at the platform level. While not all of the factory burn-in failures precipitated would have escaped and failed at the platform level, this is considered a reasonable estimate of available cost leverage based on the average defect rate of 5 failures per radar used in the calculation, which is considerably less than actual initial burn-in experience of 16 failures per radar.

It must be recognized that the cost savings projected cannot be realized without an increase in equipment manufacturing costs. The estimated size of the increase is dimensioned as follows:

$$\text{Factory Costs/Radar} = \frac{I + Q\,(T + F_1 C)}{Q}$$

$$\approx \$4000/\text{Radar}$$

This amounts to roughly 2% of the procurement costs for a radar of this type, but based on the projected savings it should be treated just as a reallocation of costs to the equipment manufacturing level, where the cost of finding and fixing failures is a minimum.

Another alternative to examine using this example is portrayed when factory screening is not performed, i.e., $I + Q (T + F_1C) = 0$ and the given five failures/radar do occur at the platform level, in the same assumed distribution; then:

$$F_A C_2 + F_E C_3 = \$17,000/\text{Radar}$$

Using the values provided in this analysis indicates that there is a possible savings of up to $13,000/Radar by performing factory LRU screening.

Also important to note is that the APQ-113 values used in the example to estimate the value of product screening are not independent of the positive effects of parts screening.

SECTION III

RELIABILITY PROGRAM ANALYSIS

A. INTRODUCTION

This section describes the APQ-113/114/144 Attack Radar reliability program elements, disciplines, and results during the RDT&E and production contract phases. The objective is to identify, analyze, and dimension the primary reliability program elements incorporated and their contribution to equipment MTBF achievement. Comparisons are drawn between the APQ-113/114/144 and the APQ-120 radar reliability programs as data availability permits. Reliability evaluation and qualification testing programs are analyzed separately in Section IV.

B. SUMMARY

- Pre-Release Program

  Analyses are made of the APQ-113 RDT&E reliability program experiences including the reliability program specifications, analytical MTBF predictions, and part standardization and application.

- Reliability Tradeoff Decisions

  The decisions presented and analyzed contributed most effectively to equipment MTBF achievement and involve the tradeoffs made in material quality levels, product complexity, and product and subcontract item environmental screening.

- Production Reliability Program

  The reliability program elements influencing, controlling, and measuring the APQ-113/114/144 manufacturing production program are evaluated. The elements evaluated include the equipment design maturity at time of release to manufacturing, the production test program structure established, the resulting failure distributions and performance measurements, and the routines utilized for technical problem identification and solution.

C. FINDINGS AND CONCLUSIONS

1. PRE-RELEASE RELIABILITY PROGRAM

a. Findings and Observations

- The APQ-113 challenging MTBF requirement and its strict customer enforcement were primary factors influencing the program direction and success.
- APQ-113 equipment MTBF initially measured in reliability evaluation test was approximately 10 percent of that predicted.
- APQ-113 part failure rates used for predicting the equipment MTBF were achieved in Reliability Qualification Test.
- Eighty percent of the parts selected for the APQ-113 radar were compliant with the prime contractor's Preferred Parts List.
- The APQ-113/APQ-120 part drawing standardization was approximately 1.9:1.
- Both the APQ-113 and APQ-120 parts were applied within their established derating criteria.

b. Conclusions

Challenging achievable reliability specifications should be derived, based on required equipment functional capability and considering optimization of RDT&E reliability program investment with projected equipment life cycle maintenance costs.

Demanding reliability requirements are essential to optimize equipment reliability capability, constrain design complexity, necessitate selection of high quality parts, and discipline parts application.

Meaningful and demanding equipment reliability performance can be achieved and demonstrated as part of RDT&E programs, if contractually specified as requirements and uncompromisingly enforced.

Analytical predictions of demanding reliability performance are achievable, using credible part failure rates, and dynamically structured reliability growth testing programs.

2. RELIABILITY TRADEOFF DECISIONS

a. Findings and Observations

- Environmental parts screening of 89 percent of the APQ-113 radar part complement was required to meet the 134-hour (at 90% confidence) MTBF requirement.

- Room ambient testing alone during manufacture of avionics products to be used in high performance aircraft environments is inadequate based on APQ-120 and APQ-113 experience.

- Failure-free cycle criterion as part of product environmental screening assures burn-in of the product and provides incentive for corrective action.

- The APQ-113 utilized approximately four times the percentage of environmentally screened parts as the APQ-120 (89 versus 24 percent).

- The APQ-113 parts screening criterion was for the most part more stringent than the APQ-120.

- The original APQ-113 design had to be simplified through parts reduction from 15,000 to 10,704 to meet the MTBF requirement.

- One hundred percent LRU temperature cycling screening was necessary to meet the APQ-113 MTBF requirement.

- One hundred percent environmental screening of subcontracted items at the subcontractor's facility was necessary to meet the APQ-113 MTBF requirement.

b. Conclusions

Equipment complexity needs to be contractually limited, consistent with functional capability, to preclude parts count escalation and its attendant negative impact on reliability, performance, and life cycle maintenance costs

One hundred percent parts screening is necessary to meet demanding reliability requirements and provide effective control of the quality of purchased materials.

Complex electronic products having demanding reliability requirements and high performance aircraft applications, must be 100 percent screened, during manufacture, in the most severe end use environment, but no less than MIL-STD-781 requirements.

Subcontracted items must be subjected to the same reliability requirements and disciplines applied to the prime equipment, and environmentally qualified as end items.

3. PRODUCTION RELIABILITY PROGRAM

a. Findings and Observations

(1) Equipment Design Maturity/Stability

- The APQ-113 design was 90 percent stabilized at completion of engineering and reliability qualification which was prior to delivery of 20 percent of the production equipment.
- The APQ-120 environmental and reliability qualification testing were not completed until approximately 80-90 percent of an order of 840 radars had been delivered.
- The more complex APQ-113 LRUs incurred a higher level of design change and took up to one year longer to reach maturity.
- The APQ-113 LRUs experiencing the highest level of RDT&E drawing change activity also experienced the greatest number of problems in both the factory and field.
- The APQ-113 RTM analog design took longer to reach maturity than the Synchronizer digital design.
- The APQ-113 mechanical design maturity lagged electrical maturity by nearly a year.

(2) Production Test Program Structure

- The APQ-113 and APQ-120 factory test programs were fundamentally similar until the APQ-113 program was upgraded.
- One hundred percent incoming test was necessary to control lot-to-lot quality variation found even on screened material.
- Eleven percent of the APQ-113 part population submitted to parts screening failed.
- APQ-113 major procurement items initially had failure rates exceeding the required system failure rate.
- Thirty percent of the APQ-113 radars were subjected to Reliability Acceptance Testing (RAT). The APQ-120 radars were not RAT tested.
- The original APQ-120 equipment test was supplemented by a six-hour failure-free ambient run-in test and a three-hour performance test.
- The upgraded APQ-113 test program structure was 98 percent effective in screening part and workmanship failures.

(3) Failure Distributions/Performance Measurements

- APQ-114 and -144 equipment configuration changes caused initial setback in equipment test defect rate performance.

- APQ-113 LRU burn-in precipitated over 45% of all LRU test level failures and 40% of all equipment level test failures.

- Seventy percent of all the APQ-113 in-process test failures occurred at subassembly test, the most cost effective point in the in-process flow to detect failures.

- The distribution of APQ-113 in-process test failures by LRU closely correlated to LRU part count complexity for the RTM and ACU. The Synchronizer and Indicator/Recorder departed from this pattern for identifiable causes.

- APQ-113 problem distribution by LRU experienced in the factory is essentially the same distribution found in the field.

- On-receipt quality (test rejection rate) of screened material is an average of 5:1 better than nonscreened.

- Screened parts quality is 10:1 better than nonscreened.

- APQ-113 part failure rates improved by approximately an order of magnitude at each test level in going from parts screening to incoming test to factory test to reliability testing.

- The combination of parts screening and 100 percent incoming test provided effective control of purchased part quality by precipitating over 90 percent of the part problems experienced.

- LRU burn-in failures generally increased with LRU part count complexity and ranged from 0.5 to 1.9 failures per LRU processed.

- Forty to 80 percent of the APQ-144 LRUs exposed to temperature cycling failed, averaging 1.5 to 2.2 failures per failed LRU.

- Approximately one-half of the APQ-144 LRUs failing burn-in failed during the first temperature cycle.

- Two-thirds of all APQ-144 LRU burn-in failures were observed at low temperature.

- Product environmental screening contributed to a 3:1 improvement in equipment reliability growth under environmental conditions through the identification and correction of pattern failures.

- Major procurement and specialty devices accounted for 20 percent of all LRU burn-in problems, failing at rates up to 100 times greater than electronic components.

- Parts, specialty devices, and major procurement items, all previously environmentally screened, accounted for approximately 80 percent of all LRU burn-in failures.

(4) Problem Identification and Solution

(a) Failure Analysis -

- Thirty percent of APQ-113/114/144 factory reported parts failures could not be verified as failed parts through laboratory failure analysis.

- Thirty-five percent of laboratory verified APQ-113/114/144 failures of screened material were supplier responsibility; the balance were induced failures for a variety of causes.

(b) Technical Problem Solving Routines -

- All program technical problems including design, material and workmanship have to be identified and resolved in a timely manner for maximum rate of equipment reliability growth.

- Effectiveness of execution and attention to detail are key factors in making technical problem solving routines work.

b. Conclusions

(1) Equipment Design Maturity/Stability

- New product designs should not be released for volume manufacture until Reliability Qualification Testing has certified that the equipment meets its specified reliability requirement.

(2) Production Test Program Structure

- The manufacturing test program structure establishes the effectiveness of product screening and the quality level of the product delivered; therefore the minimum production program test structure for complex avionics products utilized in high performance aircraft environments should be contractually specified and approved.

(3) Problem Identification and Solution

- Reliability programs must be structured to provide for the timely identification and elimination of all design, material and workmanship pattern problems in order to achieve maximum rate of equipment reliability growth.

- Measurement of equipment MTBF using unanalyzed failed part data will be biased unrealistically low, based on APQ-113 factory experience revealing that typically 30 percent of factory test reported part failures, when analyzed, cannot be verified as failed parts.

- Part failure analysis needs to be maintained throughout a production manufacturing program because of subtle design and process changes as well as lot-to-lot quality variation problems, continuously introduced by part suppliers.

- Existing electrical part screens need to be improved as typically 35 percent of the electrical test level verified failures of screened material had assignable causes attributable to supplier responsibility.

D. PRE-RELEASE RELIABILITY PROGRAM

1. INTRODUCTION

This subsection is structured to provide the background material covering the initial sequence of events of the APQ-113 reliability program. Its objective is to describe and analyze the reliability engineering disciplines that were applied during the contract design and development period. The following elements were specifically selected for analysis and discussion:

- Program Reliability Requirements
- Reliability Predictions
- Parts Standardization
- Parts Application

Where data was available, comparisons were drawn with the APQ-120 radar relative to the associated elements.

2. SUMMARY

a. Reliability Requirements

The APQ-113 MTBF requirement was technically challenging and was not initially achieved, but was contractually enforced, causing equipment redesign, material quality upgrading, test program restructuring, product environmental screening, and reliability growth testing until the requirement was demonstrated. These program elements would not have been implemented to the same degree, or at all, if the MTBF requirement had been lower or not enforced.

b. Reliability Predictions

The APQ-113 MTBF prediction based on part failure rates was achieved in equipment reliability qualification test. This was accomplished only after a substantial reduction in parts coupled with the utilization of approximately 90 percent screened material which in effect doubled the radar's analytical MTBF prediction and inherent capability.

c. Parts Standardization

Parts standardization was specifically addressed during design and development of the APQ-113 Attack Radar, as part of an Air Force Parts Standardization Program. As a result, 80% of the parts selected for the radar were compliant with the prime contractor's Preferred Parts List.

Comparison between the APQ-113 and the APQ-120 radars disclosed that on a basis of distribution of percent of part population per part drawing, the APQ-113 used approximately one-third fewer drawings.

d. Parts Application

This study showed that for the APQ-113 radar to demonstrate the MTBF requirement, essentially all parts (97%) had to be derated within 70% of the manufacturer's rating under worst case, first article environmental conditions. Data reviewed for both the APQ-113 and APQ-120 radars disclosed strict compliance to their derating criteria for part application.

3. RELIABILITY PROGRAM REQUIREMENTS

The reliability program requirements for the RDT&E or pre-release phase of the APQ-113 Attack Radar were defined in the General Dynamics specification FZM-12-041 dated 9 January 1963. This program specification was as comprehensive as MIL-STD-785 and required a development testing program, reliability pre-qualification test, and reliability qualification test to Test Level III of MIL-R-26667A. Other requirements of this specification included the establishment of a component part standardization program, a failure analysis and corrective action system, and monitoring of graphical Reliability Growth, along with standard reliability program elements of reliability prediction, modeling, apportionment, design reviews, and formal reporting.

All of the above-listed reliability disciplines and tasks were further defined and elaborated upon in a General Electric Company Reliability Program Plan for the APQ-113 Radar.

The APQ-113 contracted reliability requirement was to design and manufacture an attack radar capable of test demonstrating an MTBF of 134 hours at 90% confidence. This MTBF requirement became one of the most important factors influencing program decisions and events, and ultimately the radar's field performance.

4. RELIABILITY PREDICTION

a. Factors Applied

The APQ-113 reliability predictions were based on the following factors:

- The total number of electrical parts utilized (integrated circuits were defined as a part)
- MIL-HDBK-217 generic part failure rates supplemented by experience factors on similar equipments
- Parts failure rates computed based on the applied electrical and environmental stresses of each part as a ratio to the supplier's maximum ratings
- Parts failure rates reflecting the quality index of the parts, nonscreened parts (i.e., military standard devices, JAN, RN) versus screened parts (i.e., established reliability devices, JANTX, RNR).
- MIL-HDBK-217 procedures for redundant and/or series configurations.

b. Prediction Estimates

The MTBF prediction fluctuated as the equipment complexity changed to meet functional performance requirements. The initial projection of 3600 electrical component parts increased to as high as 18,000 component parts, before ending up at the 15,000 part level for RDT&E equipment, as denoted in Table VII.

TABLE VII. APQ-113 PARTS DATA

	[illegible]					[illegible]				
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]		[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[illegible]

[illegible]

An assessment of the reliability prediction at the 15,000 part level established that due to the growth in parts count, although partially compensated by an increased percentage of screened parts, the MTBF prediction dropped to 88 hours, significantly less than the minimum requirement of 134 hours at 90% confidence.

c. Prediction versus Initial Performance

To demonstrate this requirement in a fixed time test of 10 MTBFs or 1340 hours required measuring an MTBF of 268 hours. The initial reliability evaluation test measured performance was 11 hours* MTBF or only 10% of that predicted. This was the first insight into what was to become known as the RPM "10 Percent Rule" which is discussed in another section of this report.

d. Corrective Measures

The significant difference between the MTBF prediction of 88 hours and the contract requirement,substantiated as a problem by the test results, caused a major redesign effort. This redesign effort was directed at increasing the MTBF of the radar through reduction in the total number of electrical parts, increasing the material quality level by utilizing a higher percentage of screened parts, and reviewing each part application to confirm that optimum derating was, in fact, applied.

The initial APQ-113 production equipments, Table VII, were of the reconfigured design, having an MTBF prediction of 170 hours as a result of the following significant reliability improvements:

- The parts count was reduced by 4300 discrete parts by replacing them with 363 high speed monolithic integrated circuits (ICs) (a 60% increase in ICs).

- The percentage of screened parts was increased from 29 to 89%, enabling use of the average predicted part failure rates shown in Table VIII.

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*9.5 hours at 90% LCL.

TABLE VIII. COMMODITY FAILURE RATE COMPARISON, APQ-113 VERSUS APQ-120

	QTY/RADAR		NO. DWG. PER GENERIC PART		AVERAGE FAILURE RATE (λ)*				
					MIL-HDBK-217A		PREDICTION		OBSERVED
GENERIC PARTS	APQ-113	APQ-120	APQ-113	APQ-120	STD	HI REL	APQ-113	APQ-120	REL. TEST - APQ 113/114/144
CAPACITORS	1403	2391	50	65	1.21	0.60	0.11	0.40	0.15
DIODES	1540	1578	40	82	1.91	0.19	0.39	0.62	0.37
TRANSISTORS	1298	1342	29	84	6.68	0.67	0.45	1.46	[illegible]
RESISTORS	4237	6258	57	109	0.21	[illegible]	0.05	0.44	0.07
INTEGRATED CKTS.	960	172	14	12	2.04	[illegible]	1.20	4.68	0.63
TOTALS	9438	11741	190	[illegible]	2:1 TO 10:1				

* λ IN FAILURES PER MILLION HOURS

e. Prediction and Performance Correlation

The predicted improvement in equipment MTBF was eventually confirmed through formal reliability demonstration test whereby the APQ-113 radar production configuration equipments demonstrated an MTBF of 152 hours at the 90% lower confidence level.

The average predicted part failure rates and those observed in reliability testing are shown in Table VIII. Note that the observed transistor failure rate was nearly twice that predicted, but the IC failure rate was one-half of that predicted. The difference in IC failure rates is attributed to the insufficient test data available at the time, resulting in a pessimistic prediction. The net result was that the average observed failure rate the parts comprising over 90% of the system was equal to the average predicted failure rate.

f. APQ-114/144 Configuration

Although the APQ-114 and APQ-144 versions had increased functional capability compared to the APQ-113, the redesign goal was to maintain the MTBF demonstrated on the APQ-113 by controlling the parts count growth, and by increasing the quality level of material. The results of this effort are summarized in Table IX, showing that the parts count increased by 5 to 10% above the APQ-113 levels, and the screened material utilization increased by 2 to 3%.

TABLE IX. APQ-114/144 PARTS DATA

	APQ-114					APQ-144				
PART TYPE	NO. OF DWG	TOTAL QTY	% SCREENED	AVG PARTS PER DWG	AVG λ PRED	NO. OF DWG	TOTAL QTY	% SCREENED	AVG PARTS PER DWG	AVG λ PRED
CAPACITORS	49	1407	100	29	0.11	45	1564	100	35	0.11
RESISTORS	57	4383	100	77	0.05	72	4554	100	40	0.05
DIODES	43	1364	100	29	0.19	56	1640	100	31	0.19
TRANSISTORS	31	1317	100	30	0.45	36	1360	100	36	0.45
I.C.	19	1044	100	23	1.30	19	1081	100	60	1.30
INDUCTIVE DEVICE	59	302	100	5	0.44	61	376	100	5	0.44
MAJOR PROCUREMENT	6	7	57	1	40.00	6	7	57	1	40.00
SPECIALTY DEVICES	43	350	19	8	6.20	41	279	12	6	6.20
MISCELLANEOUS	101	766	1	8	0.67	92	776	1	9	1.35
TOTALS	404	11,162	91	26	.45	444	11,545	92	27	.41
	PREDICTED MTBF - 165 HOURS					PREDICTED MTBF - 175 HOURS				

5. PARTS STANDARDIZATION PROGRAM

a. Program Objectives

High emphasis was placed on parts standardization, from the beginning of the program, through the creation of a prime contractor's (General Dynamics) Part Standardization Board. The F-111 program was the first Air Force Avionics Weapons System to undertake an integrated parts standardization program.

As a result of GE's participation in this standardization program, 80% of the parts selected for use in the APQ-113 Attack Radar were compliant with the prime contractor's Preferred Parts List.

b. Preferred Parts Utilization

This high degree of standardization was achieved by generating a Radar Preferred Parts List (PPL), derived from the prime contractor's list. This list was distributed to all Design Engineering personnel during the initial design phase as the single approved source document for part selection. Similar parts standardization practices and procedures were required of major subcontractors.

Conformance of the Attack Radar's parts complement with the preferred parts list is graphically depicted in Table X.

TABLE X. MATERIAL QUALITY AND APPLICATION

		APQ-113		APQ-114	APQ-144
		RDT&E	PROD.		
QUANTITY OF PARTS	PER RADAR	15000	10704	11160	11545
	SCREENED - TOTAL	4350	9506	10177	10581
	SCREENED - IN-HOUSE	2469	6706	1864	257
	SCREENED - SUPPLIER	1881	2800	8313	10324
PPL COMPLIANCE (%)		70	75	82.7	85
% DERATING COMPLIANCE		75	99	99	99

c. APQ-113 versus APQ-120

The part selection program implemented on the APQ-113 Attack Radar compared with that of the APQ-120 Fire Control Radar (Figure 20) shows that the APQ-113 utilized one-third fewer part drawings and 2800 fewer parts to achieve basically the same functions.

Comparisons of part standardization are shown by part type in Figures 21 through 26. These charts show the percent of total part population of a generic part type (capacitor, resistor, diode, transistor, or integrated circuit) as a function of the number of different part drawings utilized. The 50% and 75% of total part population points were selected as meaningful points to compare the level of standardization achieved.

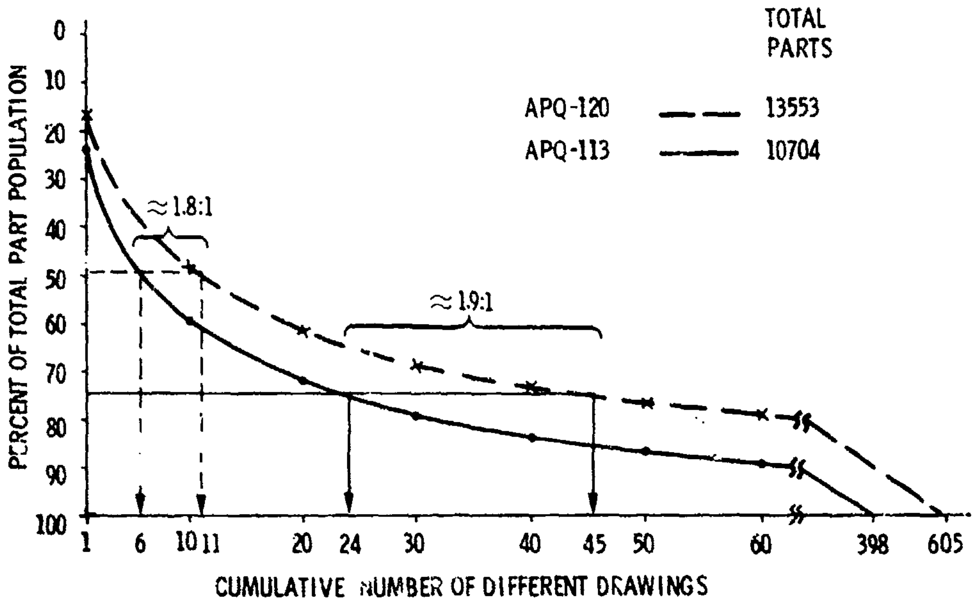


Figure 20. Drawing Standardization Comparison, Composite of All Drawings

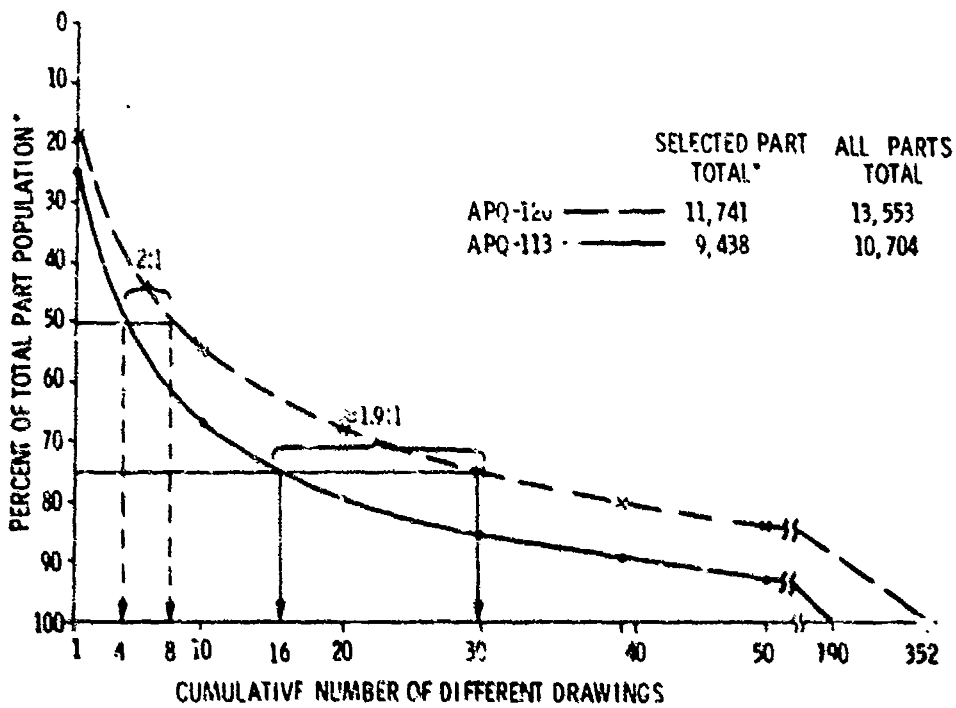


Figure 21. Drawing Standardization Comparison - Capacitors, Resistors, Diodes, Transistors and Integrated Circuits

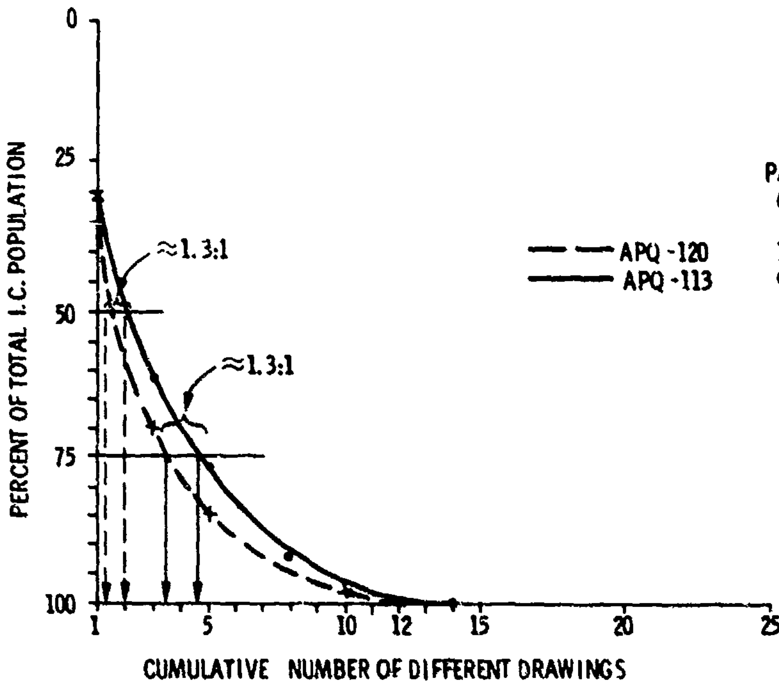


Figure 22. Drawing Standardization Comparison - Integrated Circuits

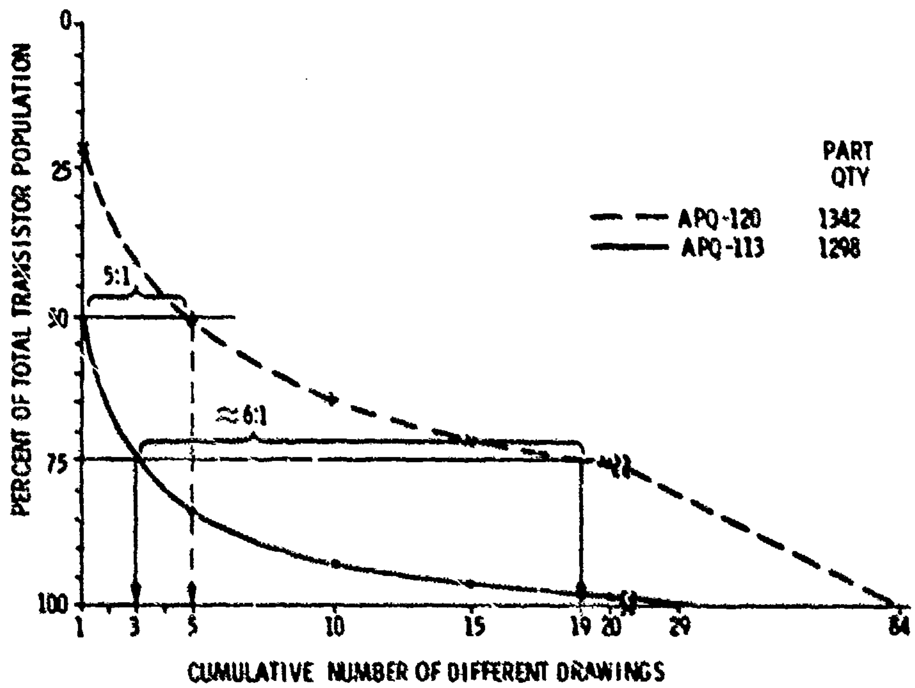


Figure 23. Drawing Standardization Comparison - Transistors

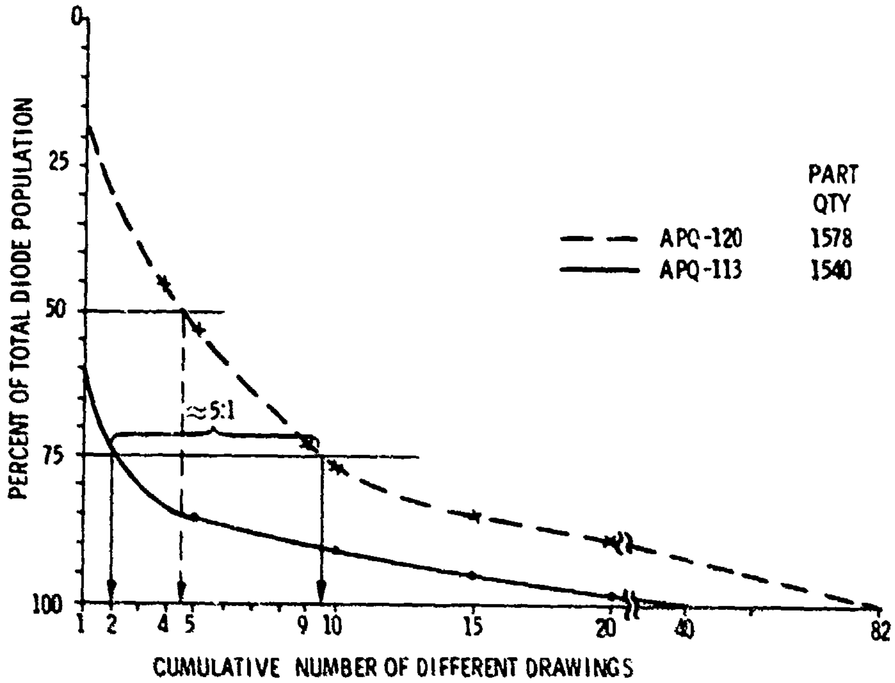


Figure 24. Drawing Standardization Comparison - Diodes

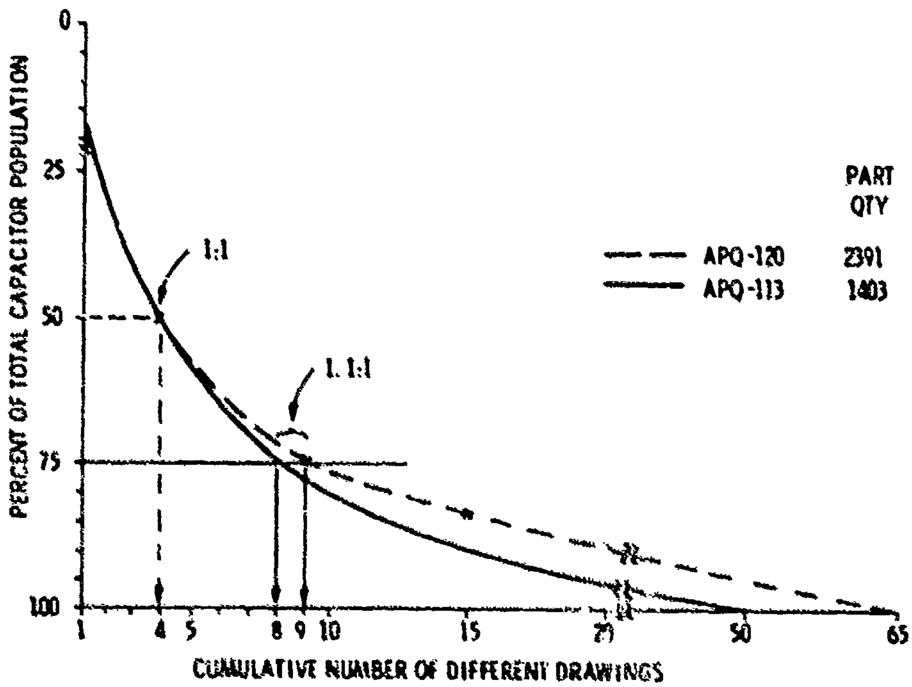


Figure 25. Drawing Standardization Comparison - Capacitors

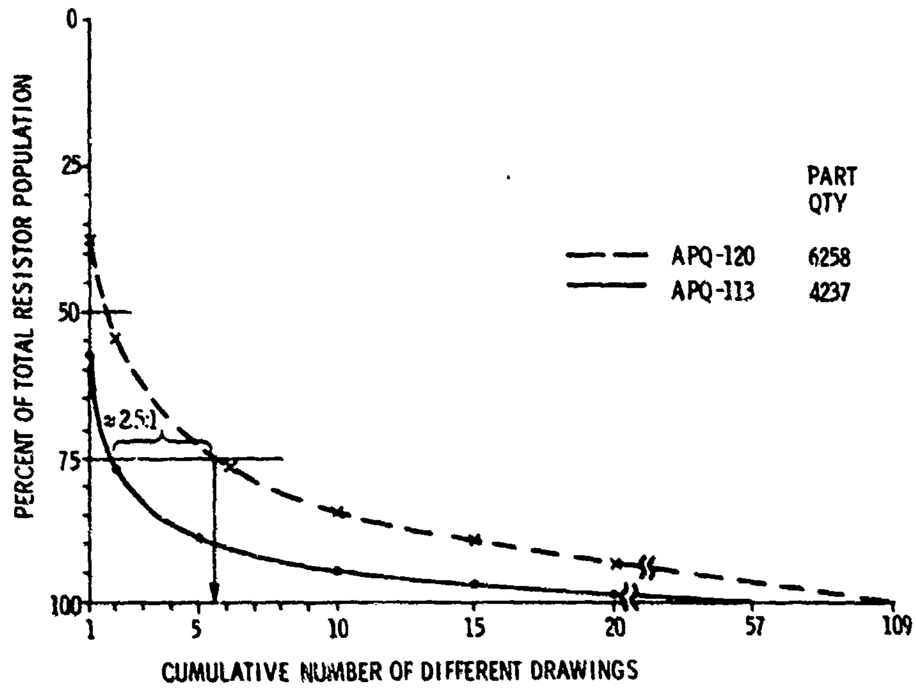


Figure 26. Drawing Standardization Comparison - Resistors

d. Cost Leverage

Figures 23 and 24, for transistors and diodes respectively, suggest the potential drawing reduction available through parts standardization. In both examples, the quantities of parts are nearly identical for both radars, yet the APQ-120 took 5 to 6 times the number of drawings to incorporate up to 75% of each generic part type population and, in total, took at least twice the number of discrete semiconductor drawings as the APQ-113.

Comparisons for other part commodities were made, but the opportunity is not as apparent due to significant differences in the part quantities utilized. Figure 27 shows an estimate of the initial potential cost savings available through parts standardization. For simplicity, the comparison was made based on only the nonrecurring technical costs of making a part drawing and releasing it for use (≈ $5000). Parts standardization cost savings for a program the scope of APQ-113 were estimated by multiplying this figure by the difference in number of APQ-113 and APQ-120 drawings. Not discussed, but significant, are savings available through pooled buy purchase agreements, which are aided by parts standardization.

. PARTS APPLICATION

a. Derating Disciplines

Parts application derating criteria were provided to designers to assure sufficient design margin in each application of the selected parts. Specifically, semiconductor

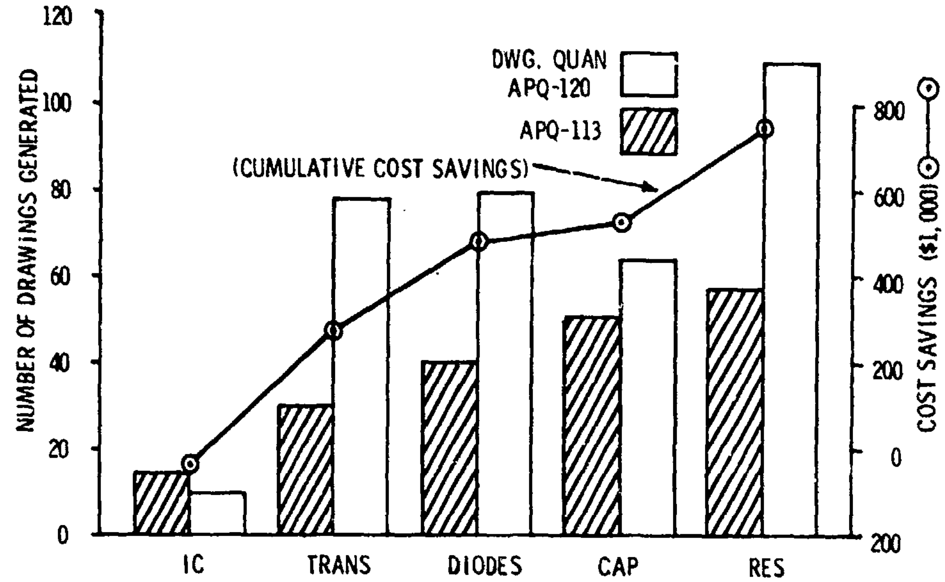


Figure 27. Parts Standardization - Cost Savings

junction temperatures were not permitted to exceed 100° C and resistor and capacitor voltages could not exceed 50% of the manufacturer's rating. Each part selected and its actual stress condition was reviewed and approved by Reliability Engineering to assure compliance to the established derating criteria. Table XI shows that over 97% of the parts used in both the APQ-113 and APQ-120 radars were applied within their established derating criteria. Because of limited data available, only 36% of the total part population of the APQ-120 radar was reviewed and, therefore, it is assumed that this quantity is a representative sample of the total radar part population.

TABLE XI. PARTS STRESS ANALYSIS COMPARISON - APQ-113/120 RADARS

PART APPLICATION STRESS RATIO (% OF MFG. RATING)	NUMBER OF DEVICES				RANGE OF DISTRIBUTION % OF TOTAL			
	APQ-113	APQ-114	APQ-144	APQ-120*	APQ-113	APQ-114	APQ-144	APQ-120*
0-69	10,422	10,896	11,308	4982	97.3	97.6	97.9	97.3
70-79	192	179	164	76	1.8	1.6	1.4	1.5
80-89	76	71	64	38	0.7	0.7	0.6	0.7
90-100	18	14	9	25	0.2	0.1	0.1	0.5
TOTALS	10,704	11,160	11,545	5121				

*BASED ON A REPRESENTATIVE SAMPLE OF 36% OF THE TOTAL PART POPULATION

A summary of the PPL and derating compliance for the APQ-113, -114 and -144 Radars is provided in Table X. Note a continuing improvement trend in adherence to these reliability disciplines in progressing from the APQ-113 to -144 design.

E. RELIABILITY TRADEOFF DECISIONS

1. INTRODUCTION

This subsection describes the technical tradeoff decisions made during the APQ-113 program, related to MTBF improvement, which affected the design, manufacture, and test of the radar equipment. The decisions determined to have the greatest reliability impact on the equipment fell into the following categories which are discussed in this subsection:

- Material Quality
- Complexity Control
- Product Environmental Screening
- Subcontracted Item - Environmental Screening

2. SUMMARY

a. Material Quality

Environmentally screening 29 percent of the APQ-113 purchased electrical parts proved insufficient to meet the MTBF requirement, since material related failures accounted for approximately one-third of the total initial reliability evaluation test failures experienced.

Extended parts screening (to 89% of the radar parts count), in intended use environments, proved effective in controlling the materials problems such that the average predicted parts failure rates were realized in reliability qualification testing.

b. Complexity Control

The APQ-113 radar failed initial reliability qualification test in a 15,000 electrical part configuration. Redesign which reduced the parts count complexity to the 10,700 level by incorporation of integrated circuits, contributed to the successful demonstration of the reliability requirement.

c. Product Environmental Screening

The ambient in-process testing plan originally implemented on the APQ-113 program proved inadequate in detecting problems which contributed to reliability qualification test failure. The problem was resolved through incorporation of LRU

environmental screening of 100 percent of production with the acceptance provision that the last two cycles of environmental exposure be failure-free.

d. Subcontracted Item - Environmental Screening

APQ-113 program experience showed that product environmental screening must be extended to the subcontract or major procurement item including all the like practices such as failure-free cycle acceptance criteria.

3. MATERIAL QUALITY

During the development of the APQ-113 RDT&E Program, a tradeoff decision was made to environmentally screen critical piece parts based on failure rate experience on other programs. Based on this decision, all integrated circuits, semiconductors, and ceramic capacitors, which represented 29% of the total parts count, were purchased to screening specifications. Despite this measure, material related problems contributed about one-third of the initial reliability evaluation features, resulting in a decision to upgrade the quality of the remaining material by increasing the number of screened parts from the 29% level to 89% of the total parts count. The correlation between the predicted parts failure rates and those subsequently measured in reliability testing attest to the fact that this screening decision contributed to the achieved equipment reliability.

The parts upgrading program was also extended to major procurement items by requiring subcontractors to use screened parts.

a. Parts versus Product Screening

One of the tradeoffs considered in lieu of upgrading the quality of material was the feasibility of continuing to use Military Standard Parts (nonscreened) and use the planned LRU level environmental screening tests, as perhaps a more cost effective approach, to precipitate failures of marginal parts. This approach was assessed and rejected for the following reasons:

- It would be impossible to stress the LRU assembled parts at their rated levels, which is where the part screening tests are effective, and therefore a percentage of marginal parts, screenable at the part level, would escape to fail at higher test levels.
- Individual part parameter drift indicative of potential latent defects could not be detected at the LRU level.
- It would not be as cost effective. Higher part failure rates of the unscreened material would increase the recurring manufacturing labor cost to troubleshoot, repair and retest the LRU, above the cost of screening at the part level.
- Identification of systematic part problems would be at a lower and slower rate at LRU test and would therefore limit the opportunity for reliability growth.

b. Program Material Quality Comparisons - APQ-113 versus APQ-120

The generic part types of the APQ-120 and APQ-144 radars were compared, to determine commonality and quality levels of the material used, in order to assess the impact of material quality level on the reliability performance differences of the two radars. Table XII shows the comparisons. For example, there are four capacitor types in the APQ-120 (Qty. 1502) that are common to the APQ-144 (Qty. 1040). Of the referenced capacitors in the APQ-120, 79% were screened; 100% of the like capacitors on the APQ-144 were screened.

TABLE XII. MATERIAL QUALITY COMPARISON, APQ-120 VERSUS APQ-144

PART CATEGORY	TOTAL QTY. APQ 120	TOTAL QTY. APQ 144	BASIC GENERIC DESIGNATION	APQ 120 QTY.	APQ 120 % OF PART CATEGORY (100 80 60 40 20 0)	APQ 144 % OF PART CATEGORY (20 40 60 80 100)	APQ 144 QTY.
CAPACITORS	2391	1583	CK	1186	576R461 576R670 576R826	7618399	326
			CS	251	CS	CSR & 3R 165 & 7060804	317
			CTM	0		7060842	225
			CL	65	CL	7618440 & 7060827	170
			SUB-TOTAL	1502			1040
RESISTORS	6258	4554	RN60	676		7736766	2385
			RC07	30		RCR	8?7
			RC20	10		RCR	182
			RL07	3378	RL & 577R536		0
			RL20	194			0
			SUB-TOTAL	4288			3404
DIODES	1578	1680	1N645/649	253	JAN	JAN TX	269
			1N914/4148	389	JAN & 577R384	7060751	999
			1N486	252	JAN & 577R378		0
			SUB-TOTAL	894			1268
TRANSISTORS	1342	1360	2N2222/2219	27	579R992	7618383	615
			2N2907/2905	214	577R561	7618403	170
			2N2369	0		7618404	105
			2N2453	261	577R387	7618402	43
			2N1893	145	576R807	7060821	56
			SUB TOTAL	647			989
INTEGRATED CIRCUITS	172	1081	HYBRID	52			13
			LINEAR	11			14
			DIGITAL	42			1054
			SUB-TOTAL	105			1081
TOTAL	11,741	10,258		7436			7782

LEGEND:
SCREENED
NON-SCREENED

Similar comparisons hold true for other parts that were found common to both radars. Of 7436 parts examined in the APQ-120, 24% were screened. Of the 7782 parts in the APQ-144 which were common to parts used on the APQ-120, 100% of the parts were screened. This difference in percentage of screened material is considered one factor contributing to the MTBF reliability performance differences of the two radars studied.

In addition to dimensioning the percentage of the parts complement that was screened, the screening specification requirements applicable to five part types common to both radars were examined. Table XIII portrays the screens used and their relative severity as applied to each referenced part type. The initial observation is that the APQ-120 resistors and diodes were not screened while the APQ-144 were. A significant difference was found in the power burn-in screen, which is called out for each of the APQ-144 part types, while it is required only for the APQ-120 capacitors, transistors, and integrated circuits. Another observation is that the power burn-in screens used for the APQ-144 are more severe in exposure time than those applied to the APQ-120. In the case of integrated circuits, the high temperature bake, and, for capacitors, the lot jeopardy requirements, the APQ-120 part screens are considered more discriminatory.

TABLE XIII. PART SCREENING COMPARISON MATRIX, APQ-120 VERSUS APQ-144

	CAPACITOR		RESISTOR		DIODE		TRANSISTOR		INTEGRATED CIRCUIT	
SCREEN	APQ-120	APQ-144	APQ-120	APQ-144	APQ-120	APQ-144	APQ-120	APQ-144	APQ-120	APQ-144
TEMP CYCLING (5 CYCLES)	-	YES	-	YES	-	YES	YES	YES	YES	YES
CENTRIFUGE	-	-	-	-	-	YES	YES	YES	YES	YES
LEAK TEST (HERMETIC SEAL)	-	-	-	-	-	YES	YES	YES	YES	YES
MECHANICAL SHOCK	-	-	-	-	-	-	-	-	YES	-
HIGH TEMPERATURE BAKE	-	-	-	-	-	-	16 HRS	48 HRS	60 HRS	48 HRS
POWER BURN-IN	24 HRS	100 HRS	-	100 HRS	-	168 HRS	96 HRS	168 HRS	96 HRS	168 HRS
LOT JEOPARDY *	4%	10%	-	10%	-	10%	30%	10%	30%	10%

*LOTS EXCEEDING SPECIFIED PERCENTAGE OF SCREENING DROPOUTS ARE REJECTED

The conclusions derived from these comparisons are that the APQ-144 part screening was more comprehensive in the percentage of parts complement screened and that the APQ-144 part screens were for the most part more stringent.

4. PRODUCT COMPLEXITY CONTROL

a. Complexity Fluctuations

Equipment parts count was found to be an important reliability factor, in that design simplification tradeoff decisions were necessary to meet the MTBF requirement. In the original APQ-113 proposal accepted by General Dynamics, a complexity of 3600

parts was projected to perform the radar functions defined at that time. As the design developed, the estimated complexity increased to 18,000 parts. A decision was then made to redesign an analog function to a digital function, replacing discrete parts with integrated circuits, and reducing the parts count to 13,500 parts. As more design details evolved, and functional requirements developed, the parts count increased to 16,000 parts until a redesign of the most complex function reduced it to 15,000 parts.

Initial Reliability Evaluation Test findings established the necessity of reducing the parts count to achieve a predicted MTBF consistent with the minimum 134 hour MTBF requirement. Design simplification was achieved by incorporating a new integrated circuit, significantly reducing the part count to 10,704 parts for the APQ-113 production equipment. How this reduction was accomplished is discussed in the Pre-Release Prediction Analysis part of this report.

This result indicates that equipment complexity, in terms of parts count, can and should be controlled as a tradeoff in meeting reliability goals. In this case, the key to part reduction was redesign to perform analog functions digitally, substituting integrated circuits for discrete parts, and in designing logic functions which could be performed by existing integrated circuits. This was a key point in 1963 due to limited availability of high speed logic integrated circuits.

b. Configuration and Complexity Changes

The APQ-114 Attack Radar was developed subsequent to the production design of the APQ-113, and was essentially a 20% increase in functional capability. The functions added were:

- North Oriented Display Capability
- Beacon Mode
- 200 Mile Range Scale
- Automatic Photography
- Bomb Mode Command

Described on Table IX, there was a net increase in part complexity of 456 parts for these functional changes. Coupled with an increase in part screening and attendant failure rate changes, the analytical MTBF increased slightly.

The APQ-144 Attack Radar was a modification of the APQ-114 design including the following changes:

- Transmitted pulse 0.2 µsec
- Receiver bandwidth increased
- Range cursor crosshair width decreased
- Display - 2.5 nautical miles
- Tilt control changed to 8:1 minimum

The net increase in part count complexity, shown on Table IX, to introduce these changes was 385 parts; again, there was no significant change in analytical MTBF fundamentally due to the increase in screened material utilized. The lesson learned is that complexity control, to be effective for reliability performance leverage, must be addressed during the pre-release design phase. Ideally, equipment complexity should be contractually limited and specified consistent with the reliability requirement.

5. PRODUCT ENVIRONMENTAL SCREENING

a. Decision to Screen

Product environmental screening was not originally planned, but when the Reliability Evaluation Test yielded a measured MTBF of 11 hours*, corrective action was needed for the 33% workmanship failures constraining reliability growth. Product temperature screening was chosen as the best approach to solving this problem, based on earlier favorable experience obtained on a previous radar program.

b. Factors Considered

The decision as to how and where to implement the screening considered the following factors:

- Equipment level(s) to be environmentally screened
- Environments: Temperature, vibration, or a combination of both
- Test Levels and Profile: Temperature extremes, vibration levels, repetitive environmental cycles, and power ON/OFF cycles
- Test Duration: Minimum number of environmental cycles
- Accept/Reject Criteria: Electrical/mechanical functional criteria, failure-free final cycle(s)

c. Alternatives Addressed

The LRU level was selected for product environmental screening over the subassembly and the equipment level, based on tradeoffs between effectiveness and cost. Screening at multiple levels was prohibitive, based on implementation and projected recurring costs.

One hundred percent screening at the subassembly level was dismissed for the following reasons:

- The quantity of radar subassemblies would necessitate the design and construction of costly test racks, equipment, and test chambers.
- It was improbable that the specific environment seen by each subassembly in its LRU could be simulated.

*9.5 hours at 90% LCL.

- Substantial workmanship related effort would necessarily follow the subassembly screening involving interconnection of subassemblies, harnesses, and LRU chassis mounted parts. The added items and workmanship would not have been subjected to the environmental screen.

Subassembly screening was imposed, however, on a few problem-prone items where the implementation costs were offset by the reduction in failure costs.

An equipment level environmental screen was also considered but was discounted primarily for the following reasons:

- The cost of the test complex required to provide a screening capability with the ability to diagnose and isolate faults was considerably in excess of the LRU burn-in facility.

- Inefficiency in the product flow resulting from the inability to process equipment until all LRUs were available would have caused production delays and higher manufacturing costs.

d. Temperature versus Vibration

Temperature cycling was selected as the LRU environmental screen over vibration, because temperature cycling was considered to represent the most severe conditions of the reliability test and specified field environments, at the minimum test implementation cost. Temperature was also considered to be the more discriminating environment, for systematic failure identification, based on the problems that had been experienced in the initial reliability evaluation testing.

e. Acceptance Criteria

The decision to require the last two burn-in temperature cycles to be failure-free, rather than just to expose the equipment to a predetermined fixed time and cycle test, provided a stimulus to reliability growth through development of corrective actions for pattern failures. The failure-free cycle requirement introduced a significant time and cost variable into production scheduling and manufacturing by impacting the time required for an LRU to pass this screen, thereby intensifying the management emphasis on corrective action.

f. Results

LRU burn-in contributed to MTBF improvement, and was cost-effective in finding the temperature related problems early. The long term benefits accrued from the identification and elimination of pattern failures, which if uncorrected, would have constrained field MTBF performance.

6. SUBCONTRACT ENVIRONMENTAL SCREENING

a. Disciplines Required

Subcontracted Major Procurement Items (MPI) must be subjected to reliability program disciplines equivalent to those implemented for the prime equipment. Environmental screening of 100 percent of production of the APQ-113 Major Procurement Items, at the subcontractor's facility, was found to be the most significant factor in achieving and sustaining the required MPI MTBF performance.

b. Product Definition

Major Procurement Items are characterized in the radar as electronically complex assemblies, frequently state-of-the-art, or intricate electromechanical devices, procured to an end item specification. Their specialized nature required procurement from a subcontractor, usually a small manufacturer, having inherently limited technical resources. Due to development and qualification costs, these are usually sole source procurements that, once committed, limit competitive leverage and flexibility of options when problems occur.

c. Items Identified

During the pre-release phase of the APQ-113 Attack Radar, the following items were categorized as MPI:

- Azimuth Rate Control Assembly (ARCA) (Electro-Mechanical)
- Tilt Rate Control Assembly (TRCA) (Electro-Mechanical)
- Servo Repeater (Electro-Mechanical)
- D/A Converter (Solid State)
- Servo Amplifier "A" (Solid State)
- Servo Amplifier "B" (Solid State)
- Camera (Electro-Mechanical-Optical)
- CRT HVPS (Solid State)

d. Major Procurement Burn-In

At the beginning of the program, Major Procurement Items were 100 percent functionally tested as end items, at the subcontractors' facilities, in a room ambient temperature acceptance test. Failure rates at LRU screening established that such testing was inadequate to assure compliance with the required product performance under environmental conditions. A decision was then made for 100 percent burn-in of the major Procurement Items at the subcontractors' facilities for the following reasons:

- Earliest point for problem detection - Finding the problem at a subcontractor's facility provided the minimum cost path to find and correct a problem.

- Maximum problem correction effectiveness - Subcontractors' engineers and management needed first-hand visibility of their products' performance in their intended use environment. The contractual feedback communication barriers were bridged and problem responsibility unquestioned.

- Subcontractor motivation - Problems found would require correction before shipment, thereby relating successful equipment environmental performance to the business objectives of meeting contractual schedule and cost commitments.

Temperature cycling screening was subsequently negotiated and imposed upon seven MPI subcontractors on 100 percent of the product manufactured. The exception was the D/A Converter where, because of subcontractor's quoted costs, it was environmentally screened at General Electric, an effective but less desirable approach for the reasons cited.

F. PRODUCTION RELIABILITY PROGRAM

1. INTRODUCTION

This subsection contains the background, experience, and analysis of the APQ-113/114/144 production equipment during manufacture, emphasizing those program elements having the greatest influence and impact on the radar equipment's reliability performance.

The program elements that are analyzed and discussed in detail in this subsection appear in the following sequence:

- Equipment Design Maturity/Stability
- Production Test Program Structure
- Failure Distributions/Performance Measurements
- Problem Identification and Solution
  - Part Failure Analysis
  - Technical Problem Solving Routines

The primary objective in analyzing these program elements is to identify and dimension the key factors contributing to the reliability growth to provide recommendations for future comparable avionics manufacturing programs.

2. SUMMARY

a. Equipment Design Maturity/Stability

The APQ-113 equipment design released for manufacture was mature in that 90 percent of the drawing change activity was complete by the end of engineering and reliability qualification testing, which also occurred before 20 percent of the production equipment had been shipped.

b. Production Test Program Structure

The APQ-113 and APQ-120 production test programs were originally similar but the APQ-113 was significantly revised when the inital structure proved ineffective, due to inadequate screening of material and workmanship problems. The revision was accomplished by going to essentially 100 percent parts screening, 100 percent incoming test, and subcontracted item and product burn-in.

c. Failure Distributions/Performance Measurements

The APQ-113 equipment level test performance improved from an initial average of seven failures per radar to less than one. Redesign of the APQ-113 to the APQ-114 configuration caused an initial setback in the measured performance that was approximately equal to the percent of change introduced.

The APQ-113 extended parts screening proved effective by providing an average initial part failure rate advantage of ten-to-one over nonscreened parts. However, parts related failures were still predominant at nearly all levels of factory test.

Experienced parts failure rates improved by an average of an order of magnitude at each test level from parts screening through and including reliability acceptance testing.

Product environmental screening was effective as it accounted for 40 to 50 percent of all failures precipitated at all factory equipment test levels.

Mature APQ-144 equipment achieved a 3:1 improvement in LRU defect rate over the initial APQ-113 equipment, under the environmental test conditions of product burn-in; this was attributed to the identification and correction of pattern failure sources promoted through the failure-free cycles requirement.

d. Problem Identification and Solution

Laboratory part failure analysis accelerated the rate of APQ-113 equipment MTBF growth through timely and correct diagnosis of failure causes for effective corrective action. Effectiveness of execution is the primary key to successful technical problem solving routines. However, as a minimum, the routine needs the following characteristics: It must be simple to understand, adequately define and dimension the problem, assign responsibility for the problem solution, measure the progress and effectiveness of the solution, and cross functionally integrate and communicate the problem nature, impact and solution.

3. EQUIPMENT DESIGN MATURITY/STABILITY ANALYSIS

a. Introduction

Release of a marginal, incomplete, or unqualified design to production for any reason commits both the manufacturer and customer to potential unwarranted risks in terms of compromised equipment performance, excessive manufacturing and life cycle costs, and reduced weapons system availability and effectiveness.

Initial equipment MTBF performance is established and constrained by the quality and maturity of the design as released to manufacture, the quality of materials selected, and the workmanship performed. Another section of this report shows in initial reliability evaluation testing that design, materials, and workmanship each contribute to approximately one-third of the problems experienced.

This part of the Production Manufacturing Program subsection relates the design maturity status of the APQ-113 equipment to the volume and time phasing of the engineering drawing change activity.

b. Early Design Stability

The APQ-113 drawing change activity depicted in Figure 28 shows that a 90 percent stabilized design had been reached by the completion of Engineering and Reliability Qualification testing. Completing Reliability and Engineering Qualification testing early provided for incorporation of test identified corrective actions before 20% of the production radars were shipped. The timely qualification test certified design, and resulting drawing change stability, minimized the product configuration change impacts on manufacturing. In addition, having developed a mature radar early avoided subsequent extensive retrofit of fielded equipment. Other by-products of the early product maturity were minimized factory failures and rework enabling delivery of high quality conforming equipment.

c. Complexity and Change Activity

The more complex APQ-113 LRUs, the RTM and Synchronizer, had the highest level drawing change activity and the RTM took about one year longer to reach design stability. The RTM had the highest initial drawing change activity during development (Figure 28). This is attributed to its analog design and high power circuitry. However, as learned in this study, the RTM also experienced the highest percentage of system problems at all levels of factory test, and in the field, which indicates that RDT&E drawing change activity can be as early predictor of relative product factory and field performance. Accepting this fact would enable both the manufacturer and the customer to recognize potential problem-prone units and take early preventative action. Plotting the frequency of occurrence of RDT&E drawing change activity versus calendar time could also provide an estimate of the degree of equipment design maturity and stability useful in assessing the equipment's readiness for release for production.

The one-year lag in the peaking out of the RTM drawing changes (Figure 28), in relation to the Synchronizer, is an indication of the relative difficulty of designing and packaging high powered analog circuitry as compared with that of disciplined low power digital circuitry (Figure 29).

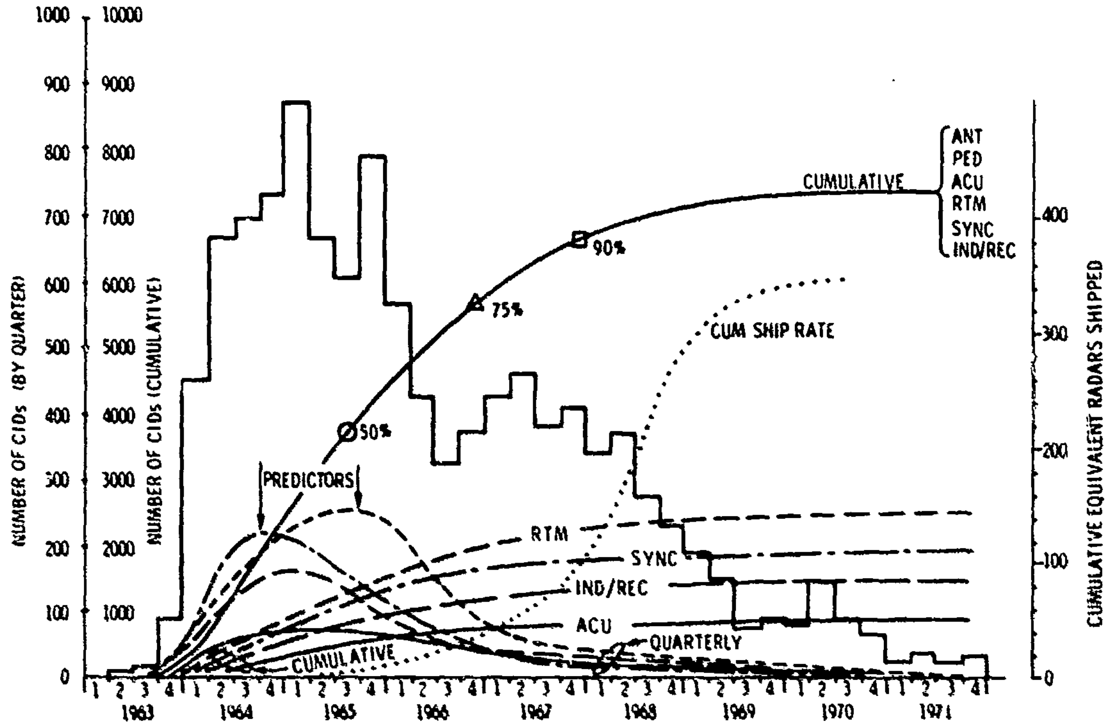


Figure 28. APQ-113 CID Activity by Quarter and Cumulative

d. Mechanical versus Electrical Maturity

Mechanical design maturity, as measured by numbers of drawing changes, lagged electrical maturity by nine months (Figure 30). From the beginning of the program, mechanical design changes outnumbered electrical by two to one.

Factors accounting for the longer time to stabilize the mechanical design, as compared with electrical, include the increased emphasis placed on resolving electrical performance problems as opposed to that placed on mechanical problems which were mainly producibility related with the exception of the antenna. Electrical problems are quickly identified in comprehensive test programs and must be immediately corrected to continue equipment processing and deliveries. Mechanical producibility changes are usually more difficult to incorporate, and do not require immediate effectivity; consequently they are accumulated for block change efficiencies.

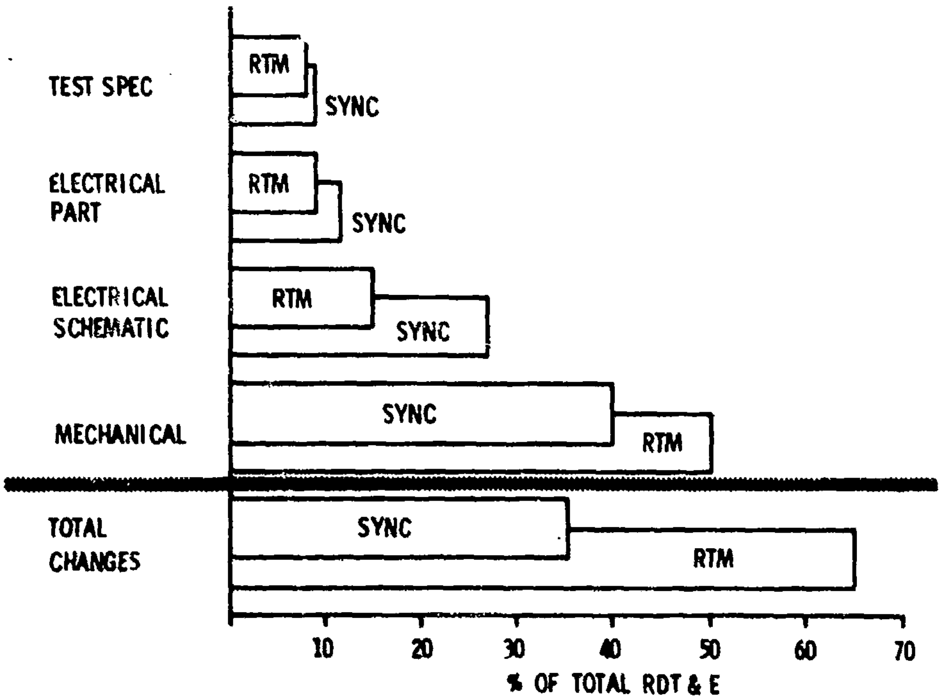


Figure 29. Drawing Change Analysis, APQ-113 Synchronizer (Digital) versus RTM (Analog)

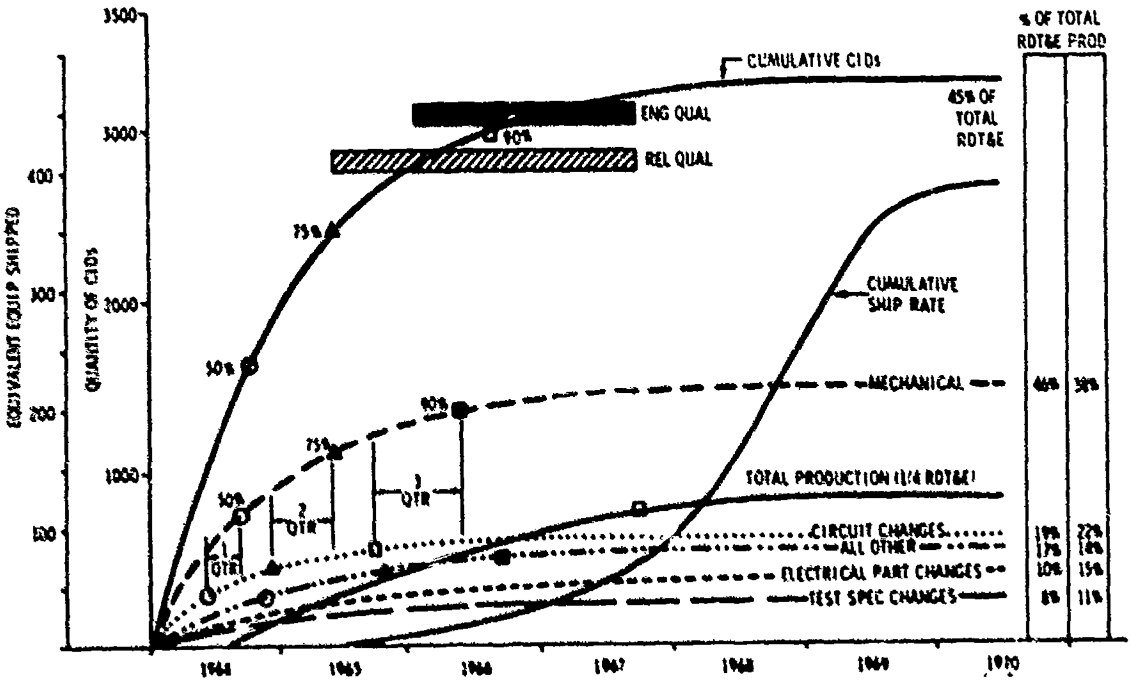


Figure 30. Drawing Change Classification, APQ-113 Synchronizer and RTM

4. PRODUCTION TEST PROGRAM STRUCTURE ANALYSIS

This part of the Production Manufacturing Program subsection describes the APQ-113 production test program structure as originally implemented and discusses the changes evolved to strengthen the program concentrating on the following elements:

- Original Concept
- Program Upgrade
- Purchased Material Control

  On-Receipt Testing
  Parts Screening
  Subcontracted Item Environmental Screening

- In-Process Testing

  Subassembly Test
  LRU Test
  Product Environmental Screening
  Systems Test
  RAT Test

- Test Program

  Part Failure Experience
  Test Level Screen Effectiveness
  Workmanship Screening Effectiveness

a. Original Test Structure

A comprehensive documented quality system established the disciplines for the production manufacturing program. Among these disciplines was the APQ-113 production test flow outlined in Figure 31, structured to assure delivery of a high quality conforming product. The elements listed in each block depict the initial scope of testing planned at each point in the production program flow. The program elements within the blocks of the flow diagram were originally similar for both the APQ-113 and APQ-120 radars.

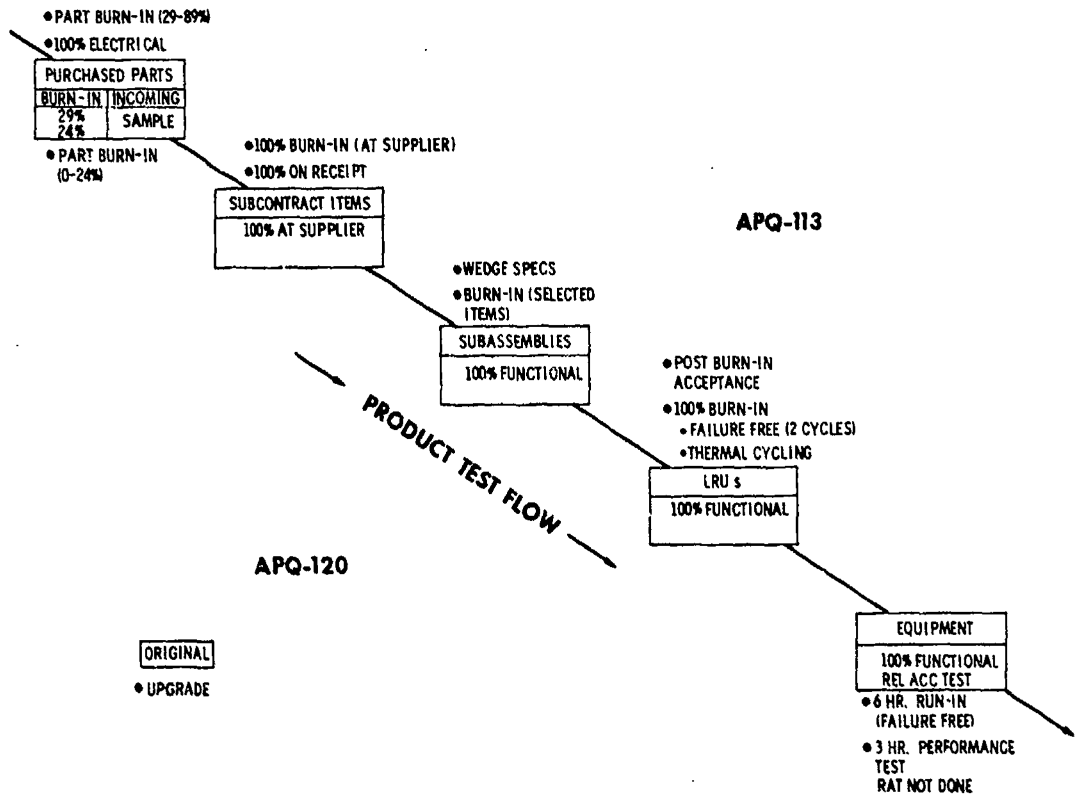


Figure 31. Product Test Comparison, RDT&E and Reliability Upgrade

b. Program Upgrade

After initial APQ-113 Reliability Evaluation Test results, it was recognized that the test program as originally structured did not screen marginal material or manufacturing workmanship induced problems effectively enough to meet the program reliability requirements. Corrective action was implemented, modifying the APQ-113 test program, as shown by the additional screens listed above each block. Reported changes to the original APQ-120 test program structure are shown just below the blocks. The revised APQ-113 test program structure provided for defect detection and

elimination, as early as practicable in the flow, through emphasis on temperature screening of parts and equipment.

c. Purchased Material Control

(1) On Receipt Testing

Initially, on the APQ-113 program, purchased electrical components were accepted at incoming test and inspection in accordance with a quality test plan specifying either 100 percent or lot sampling depending on the type of material, application criticality, or supplier quality history (Figure 31).

The typical test sampling plan for semiconductors was a 0.65% AQL with a minimum sample size of 60 pieces while all other electrical piece parts, with the exception of microcircuits, were tested to a 1.0% AQL. Microcircuits were 100% functionally tested after passing a 1.0% sample test for specific device parameters such as output voltage levels, leakage currents, and switching characteristics.

The material control plan was restructured as part of the corrective action to upgrade material quality, by the incorporation of 100 percent incoming testing of all electrical piece parts. The initial result was a marked increase (see Figure 32) in the proportionate share of defects detected at Incoming, with respect to the volume received on the APQ-113, as compared to other programs. Incoming microcircuit test capability developed during this period enabled testing of all DC and dynamic characteristics on the APQ-113 devices. One result of this testing and associated corrective action was a reduction in Incoming rejection rate on microcircuits from 15% to 5% during the first six months. Figure 32 shows the results achieved through corrective action, in that the APQ-113 Program experienced less than a proportionate share of the on-receipt rejections in 1968 and 1969 when compared to other programs.

Eventually, the Incoming rejection rate for the APQ-113 Program material was less than all other programs (Figure 33) which is attributed to the effort applied to the control of material quality early in the program (1966, 1967). The data shows the resistor rejection rate higher for the APQ-113 Program, only because of the more extensive testing conducted at Incoming, including temperature cycling, to precipitate drift failures on metal film resistors.

(2) Parts Screening

(a) Initial Program - Environmentally screened semiconductors were procured from the beginning of the program with microcircuits being 100% screened, transistors 94%, and diodes 87%. In terms of total radar electrical piece part count, however, only 29% of the parts were screened.

Even with screened semiconductors, approximately one-third of the failures in reliability evaluation testing were attributed to materials quality. To resolve this problem required either individual part corrective action, or across-the-board material controls to be maintained on a recurring basis. The latter course was taken by extending piece part environmental screening and tightening the incoming electrical test screen (Figure 31).

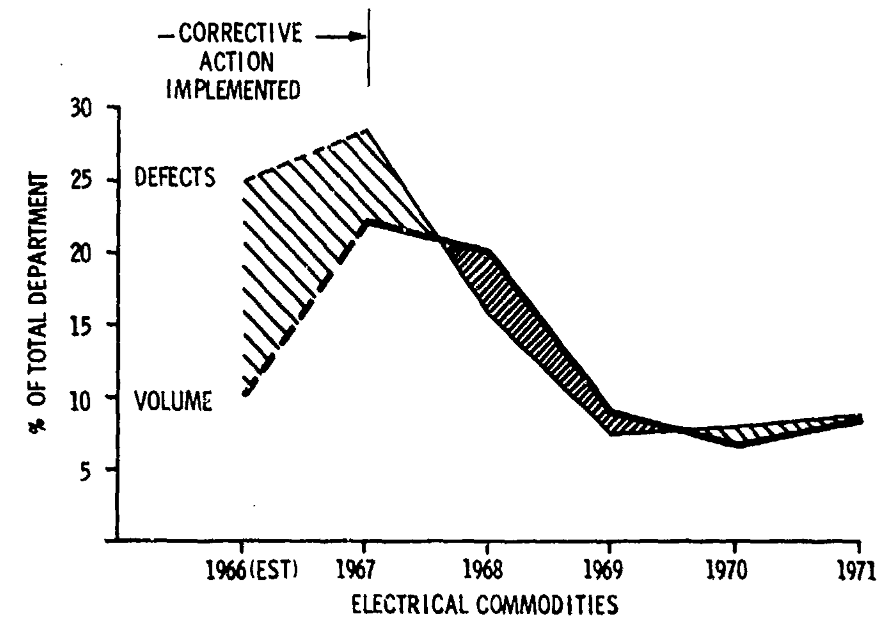
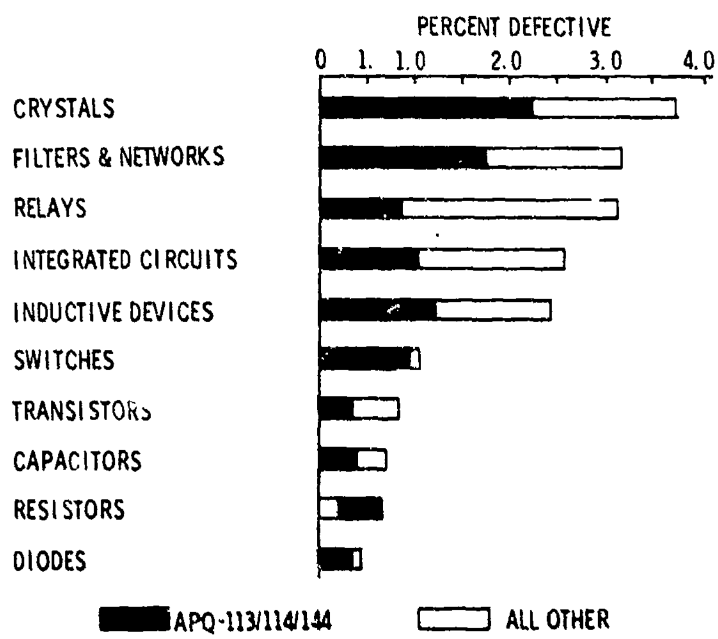


Figure 32. Incoming Material Performance, Volume versus Defects, APQ-113/114/144



APQ-113/114/144 %	ALL OTHER %
2.27	3.76
1.75	3.19
.81	3.18
1.04	2.61
1.25	2.47
.92	1.05
.34	.82
.38	.72
.7	.36
.35	.44

Figure 33. Incoming Test Experience, APQ-113/114/144 versus Other, 1967-1971

(b) Extended Parts Screening - The objective of Extended Parts Screening was to extend the application of screened electrical piece parts within the radar from 29% to nearly 100%. The time phased implementation of this program with the corresponding growth in system complement of screened material is shown in Figure 34.

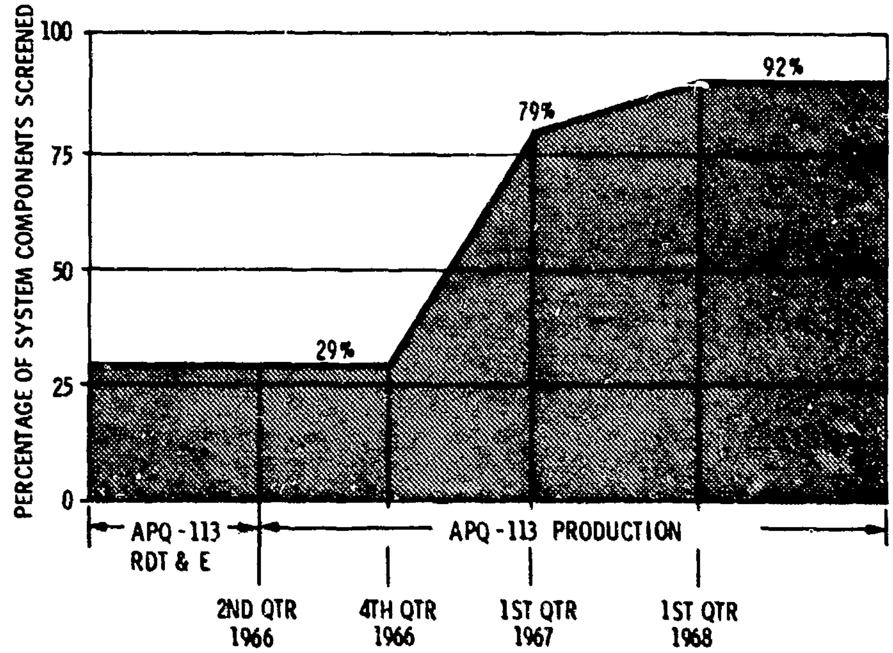


Figure 34. Extended Component Burn-in Effectivitv

An in-house screening capability was developed in October 1966 because supplier screened material was not available, or the supplier was either unable to respond to schedule needs or the price for screening was excessive.

Substantial General Electric Company investment was provided to establish the in-house parts screening capability. Included in the initial cost were the special test equipment, temperature chambers, area facilities, increased material cost, and parts drawing upgrade. The screening facility developed was capable of screening all generic part types, except microcircuits, at a six radars per week rate. The screening program utilized incoming test capability wherever possible; however, the screening performed was in addition to incoming test.

Every device was tested in the same sequence, both before and after environmental exposure, and data was recorded automatically on punched paper tape, using in-house designed and constructed Data Loggers. Drift criteria, established for each device type, determined the part's acceptability.

The screening varied within the generic part category, depending on part application and problems detected through in-process test and failure analysis. Table XIV describes the basic screening sequence for all device types as documented in screening

TABLE XIV. PARTS SCREENING PRACTICES, APQ-113/114

SCREENING OPERATION AND SEQUENCE \ PART TYPE	INTEGRATED CIRCUITS	TRANSISTORS	DIODES	SCR'S	RESISTORS	CAPACITORS	TRANSFORMERS	INDUCTORS	FILTERS
100% RECEIVING INSP. (ATTRIBUTES)									
100% LEAK TEST (HERMETIC SEAL)					NA	NA	NA	NA	NA
100% X RAY	NA	NA		NA	NA	NA	NA	NA	NA
100% MECHANICAL INSPECTION									
100% SELECTED PARAMETER MEASUREMENTS		NA	NA	NA					
100% TEMP. CYCLE -55 TO + 25/125/200°C	5 CYCLES								
100% SELECTED PARAMETER MEASUREMENTS			NA						
100% REVERSE BIAS BAKE 150/175°C	48 HRS		NA	168 HRS	NA	NA	NA	NA	NA
100% SELECTED PARAMETER MEASUREMENTS	NA			NA	NA	NA	NA	NA	NA
100% POWER BURN-IN 25 TO 125°C	168 HRS			NA	100 HRS				
100% SELECTED PARAMETER MEASUREMENTS									

(shaded) = NA

(blank) = APPLICABLE

specifications for each generic part category, which were the same in-house as for the suppliers, including lot jeopardy requirements. The lot jeopardy requirements for in-house screened devices were negotiated with the suppliers so that there was no question of responsibility for defective lots. On supplier screened devices, it was necessary to review the screening data because material was received exceeding lot jeopardy requirements.

By early 1967, 79% of all APQ-113 electrical components were being screened either in-house or by a supplier. In-house screening reached its peak in 1967 and 1968. By this time, industry component suppliers had implemented screening facilities; therefore, when it became cost effective, screening responsibility was transferred to the supplier. Table X illustrates this trend in returning screening responsibility to the supplier where problem identification and corrective action is more timely and effective. With the start of the APQ-144, approximately 89% of the material was supplier screened.

Piece part screening proved effective in identifying pattern part problems and in removing infant failures and marginal material, as illustrated in Table XV, where screening fallout was nearly 300,000 parts, or an average of 11% of the population screened during the years 1967, 1968, and 1969. This represents an equivalent of 26 radars' worth of material in this period that was discarded at the earliest and most effective point in the process.

TABLE XV. PARTS SCREENING EXPERIENCE - 1967 TO FIRST QUARTER 1969

DEVICE TYPE	APQ-113 & APQ-114		REJECTS	
	TOTAL NUMBER SUBMITTED	TOTAL NUMBER REJECTED	% OF TOTAL	HIGHEST % OF A LOT
INTEGRATED CIRCUIT	319,289	43,104	13.50	94
TRANSISTOR	508,119	68,596	13.50	75
DIODE	735,313	133,827	18.20	50
RESISTOR	830,360	41,518	5.00	90
CAPACITOR	306,895	5,831	1.90	68
TOTAL	2,699,976	292,876	10.85	--

(3) Subcontract Item Environmental Screening

(a) Initial Program - MPI subcontractor production equipment performance was initially measured through 100 percent end item ambient acceptance testing witnessed at the subcontractor's facility by Quality Control subcontract specialists during periodic surveillance visits (Figure 31). After the MPIs were accepted, severe problems were experienced ranging from rejection at incoming test, through frequent catastrophic failure at all equipment test levels, to subtle performance degradation upon environmental exposure in radar equipment tests. Two specific examples, the Camera and D/A Converter, each had failure rates which exceeded the allowed radar reliability demonstration test failure rate.

(b) Action Taken - Substantial technical support was provided to the subcontractors. They were advised of, or provided outright, General Electric Aerospace Electronic Systems Department's part selection practices, circuit design improvements, failure analysis support, and quality control assistance. This effort resulted in improvement in MPI delivery rates with items having the ability to pass short duration room temperature acceptance tests. However, there was still an unacceptably high equipment in-process test failure rate. This would not permit meeting the reliability qualification test requirements, where MPIs had to be essentially failure-free for relatively long periods at various environmental test levels.

The corrective action implemented had fixed only the gross MPI quality and design deficiencies initially experienced, leaving the subtle quality problems associated with the MPI subcontractors' manufacturing operations, and in some cases, lot problems with piece part electrical commodities. It was also increasingly difficult to obtain subcontractor corrective action, especially for those failures during LRU environmental screening, since the subcontractor's position was that the items had been accepted, according to specification, which required only a short duration functional acceptance test at room ambient temperature.

(c) Burn-In Initiated - To identify problems before installing the MPI in an LRU, temperature cycling burn-in of two of the items (the D/A Converter and HVPS) was initiated at General Electric. In parallel, and while negotiations were started to screen all of the MPIs at the subcontractor's facilities, 100 percent on-receipt testing was instituted providing the capability of verifying the subcontractor's test results, and equally as important, the capability to efficiently verify and troubleshoot failed items from higher test levels.

(d) Results Experienced - The effectiveness of subcontractor temperature screening is illustrated by the LRU burn-in failure rate improvement of two of the most problem-plagued MPIs, the Camera and Indicator HVPS, after implementation of subcontractor burn-in. The Camera experience is depicted in Figure 35 which shows the failure rate in LRU burn-in as a function of calendar time. Early poor Camera performance was indicative of initial design problems, followed by inadequate control of manufacturing workmanship. Substantial improvement was achieved by mid-1967, but an unacceptably high failure rate plateau persisted. Upon imposition of the subcontractor environmental screening, the failure rate dramatically reduced by a factor of approximately 6.

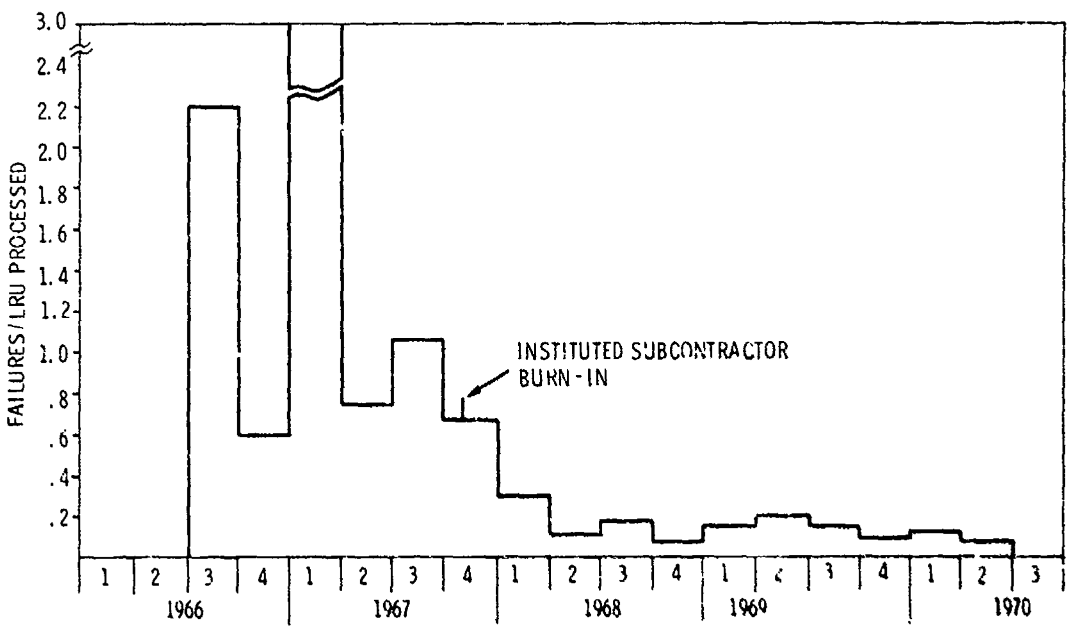


Figure 35. Camera Failure Rate at LRU Burn-in, APQ-113

The HVPS failure rate at LRU burn-in (Figure 36) increased through the third quarter of 1967 due to early design problems, poor workmanship and concurrent problems, such as faulty component piece part lot problems, and the inability of the subcontractor to provide effective corrective action. During the increasing failure rate period, actions being taken actually degraded the performance because "corrective" action effectiveness was not adequately test validated by the subcontractor prior to incorporation. The increasing failure rate shown on this chart also points out the limited effectiveness of MPI environmental screening being performed by the equipment manufacturer, because the HVPS was screened at the MPI level at General Electric from late

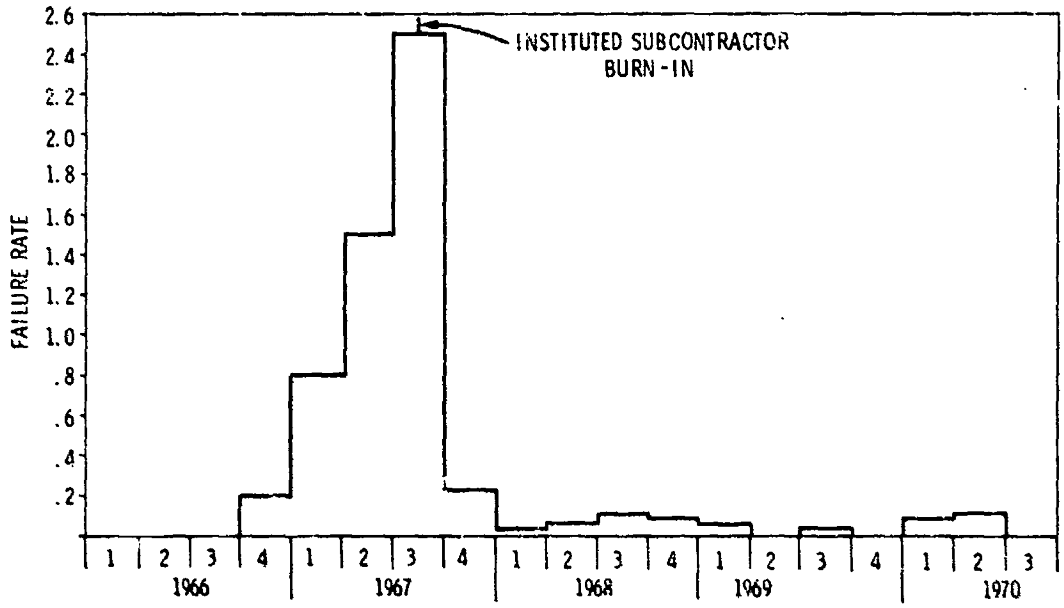


Figure 36. HVPS Failure Rate at LRU Burn-in, APQ-113

1966 to the start of subcontractor screening. Figure 37 documents the problems experienced from the start of burn-in at General Electric and the extent of technical assistance provided to the subcontractor in the solution of those problems. In retrospect, it illustrates the need for control of subcontracted products using all of the practices, procedures, and disciplines applied to the prime equipment. Following imposition of subcontractor screening, an order of magnitude failure rate improvement was achieved in a relatively short period.

d. In-Process Testing

(1) Subassembly Test

Subassemblies were wire-checked, then 100 percent functional tested to filter out process problems, manufacturing errors, and defective parts, at a point in the in process test structure where rework costs are minimal (Figure 31). As part of the upgrading restructuring of the test program, a wedge specification system, or a tolerance funnel screen, was developed to provide additional circuit performance margins at the subassembly level to assure minimum circuit compatibility problems at the higher LRU test levels, particularly under the environmental conditions imposed at LRU Burn-In.

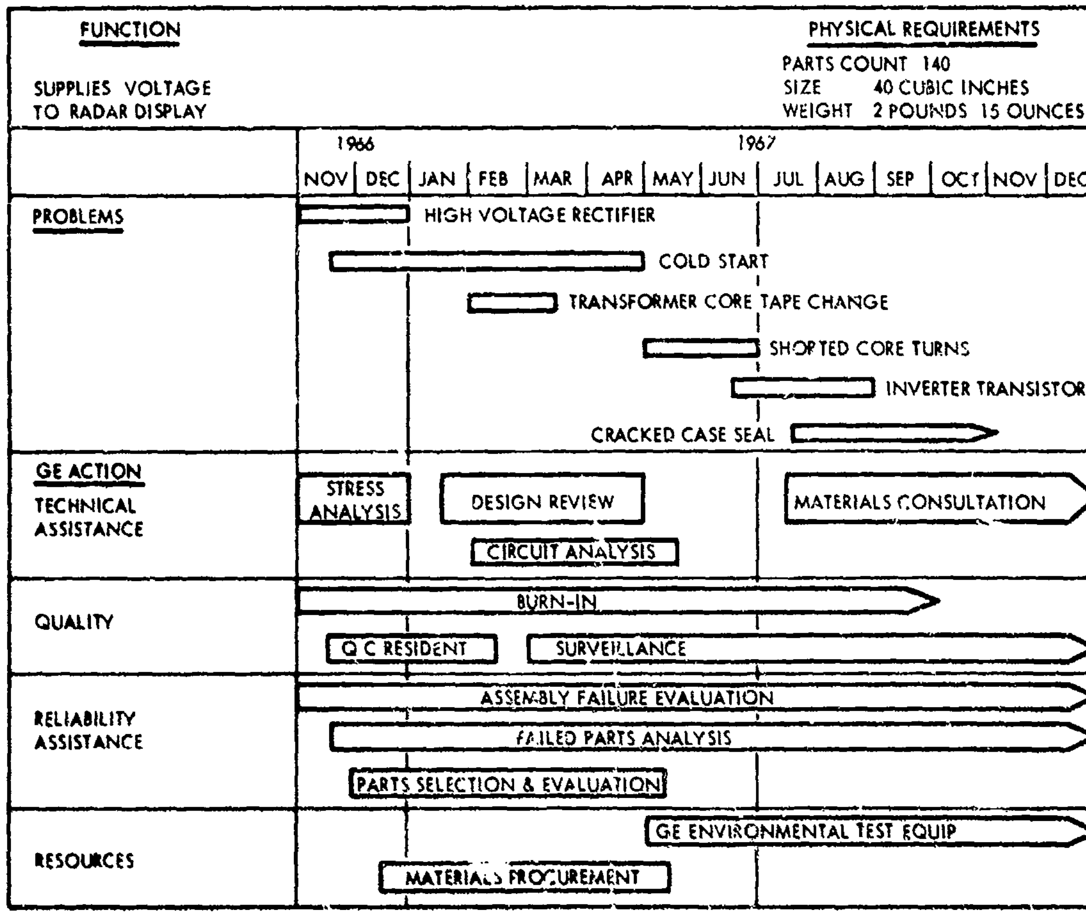


Figure 37. Major Procurement Problem Plan, APQ-113 Indicator Power Supply

(2) LRU Test

Initially 100 percent ambient functional testing at LRU level (Figure 31) was believed adequate because an LRU was comprised of a cabinet with wire checked components and harness, pretested plug-in subassemblies and Major Procurement Items Being only a higher order assembly of all these previously tested items, the LRU test was structured to measure the performance of the integrated components prior to systems level test. Reliability evaluation test established the need for an equipment environmental test screen to detect subtle manufacturing induced problems. This screen was implemented at the LRU test level based on cost effectiveness tradeoffs.

(3) Product Environmental Screening

A temperature cycling burn-in was added at the original LRU test level (Figure 31), dividing the LRU test into three distinct operations. A minimum operational test was devised, for cost effectiveness before burn-in, to provide assurance that the LRU functioned properly before installation into the environmental chamber. The burn-in test itself consisted of LRU operation during ten cycles of temperature exposure with the constraint that the last two cycles be failure-free. The post burn-in LRU test, after removal from the environmental chamber, consists of a complete functional test which is a comprehensive expansion of the acceptance test specification.

(a) Burn-In Environment - The six major LRUs of the APQ-113 Attack Radar processed through Environmental Burn-In are the Antenna, Pedestal, Antenna Control Unit, Synchronizer, Indicator/Recorder, and the Receiver-Transmitter-Modulator. The Tracking Control Unit, Radar Control Unit, and the mounting rack were not subjected to burn-in owing to the small number of electrical parts and the absence of active components.

In total, for the APQ-113, APQ-114 and APQ-144 Program, 3372 LRUs (562 equivalent radars) were processed through burn-in. During this period, the LRUs were subjected to 127,000 hours of environmental exposure while accumulating 70,000 hours of operating time.

All LRUs regardless of whether they were to be processed as spares, equipments, or eventually as Reliability Demonstration Systems, were subjected to the same burn-in disciplines consisting of temperature excursions which are similar to qualification test levels.

Figure 38 depicts the two different temperature profiles utilized in the test. The first profile is for that equipment mounted in the cabin and equipment bay areas of the aircraft, the second profile is for that equipment mounted in the radome area. Burn-in temperature levels for these LRUs are as follows:

Antenna Pedestal Antenna Control Unit	-30° F to +205° F (Radome)
Synchronizer Receiver-Transmitter-Modulator	-65° F to +160° F (Equipment Bay)
Indicator/Recorder	-65° F to +160° F (Cabin)

Cooling air is also supplied to the LRUs under test as depicted in Figure 38. The cooling air flow for each LRU is a fixed flow rate, determined by the minimum flow requirements, for each LRU at its maximum operating temperature.

The temperature of the cooling air is determined by the test chamber temperature. When the chamber temperature is below room ambient temperature (75° F), cooling air is supplied from the test chamber in order to thermally stabilize the unit. When the chamber temperature exceeds room ambient temperature, cooling air at 75° F is provided to the units under test.

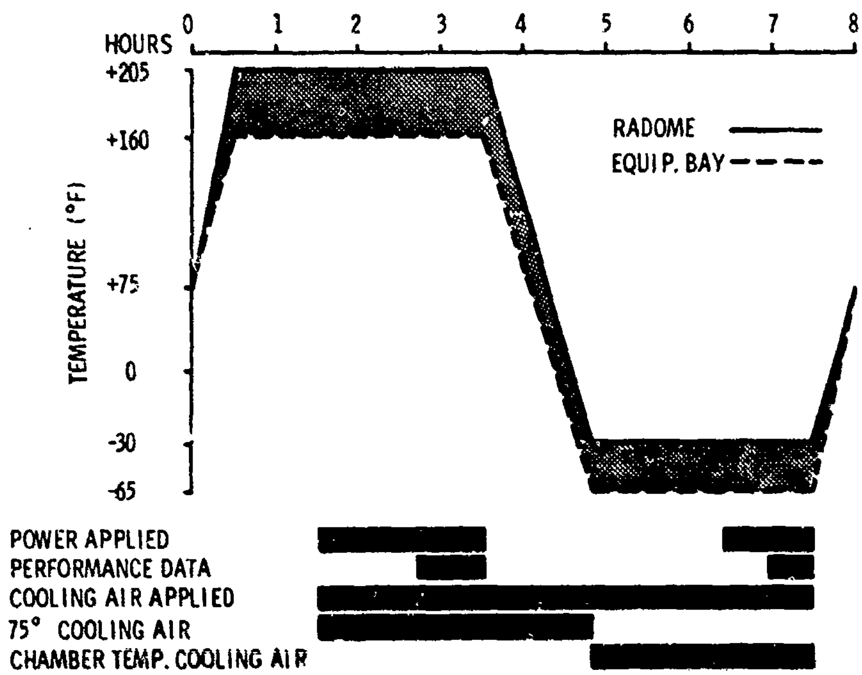


Figure 38. LRU Burn-in Test Cycle, APQ-113

The total environmental exposure received by an LRU was dependent on its failure performance burn-in. When burn-in was first imposed on the APQ-113 Program in 1965, the exposure criteria required that each equipment be subjected to 10 environmental cycles with the constraint that the last two cycles must be failure-free. Each cycle was of 8 hours duration. Figure 39 depicts the average number of cycles of burn-in encountered on the various LRUs throughout the program. The vertical arrow indicates the range of cycles which were required to complete the two-cycle failure-free criteria. The dots on the arrows indicate the average number of cycles required during that portion of the program. Note that on the APQ-113 Program as many as 22 cycles were required to complete the two-cycle failure-free criteria. This trend was significantly reduced as production quantities increased and the design matured.

Throughout the program, burn-in performance was monitored for failure trends and LRU performance. Problem detection and implementation of corrective action in the early portion of the program had a dramatic effect on the number of environmental cycles required to obtain two failure-free cycles. As this average decreased, the 10-cycle criteria was re-appraised and in August 1967 it was reduced to 4 and 6 cycles.

The Antenna Control, for example, in the early APQ-113 Program proved to be a problem unit and required as many as 22 cycles to attain the two required failure-free cycles. A problem existed in the ACU with two electro-mechanical assemblies which caused repetitive burn-in failures. This portion of the ACU was redesigned and the electromechanical assemblies were replaced with solid state circuitry. This action is typical of those encountered which impacted the early failure rate of the radar.

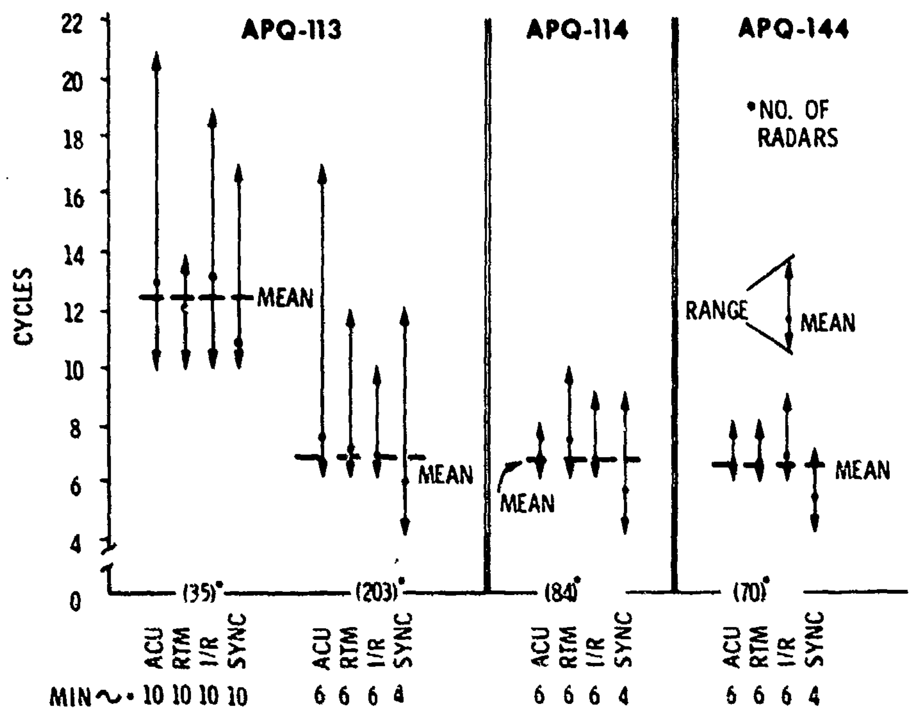


Figure 39. LRU Burn-in Cycle Performance

Burn-in test stations were implemented by LRU with each station consisting of an environmental chamber fixtured to accept 4 to 6 LRUs, and a special test station with the capability to stimulate all units simultaneously and measure the units sequentially.

The test chambers utilized primarily employ mechanical refrigeration and can achieve a temperature range of +250°F to -80° F with a rate of change of 5° F per minute. CO_2 boost is available to achieve greater rates of change or to act as backup to the mechanical refrigeration in the event of failure. Each test chamber was fixtured to house multiple quantities of an LRU. The fixturing was designed for ease of mounting and simulated the aircraft mounting for attachment points, electrical connections, and cooling air inlets.

The test equipment utilized to provide the electrical stimulus to the unit under test is similar to that utilized during acceptance testing. The equipment is modified, however, to provide stimulus to all the units under test simultaneously. Quantitative tests are conducted sequentially on each unit to determine performance under environmental stress. The extent of equipment performance monitoring capability during burn-in must be adequate to assure detection of temperature-sensitive failures, or intermittent conditions, which will go unnoticed in subsequent ambient testing and escape to fail, perhaps in fielded equipment.

Figure 40 is a photograph of the Synchronizer Burn-in Facility. The placement of each of the LRUs is such that easy access may be attained in the event that in-place

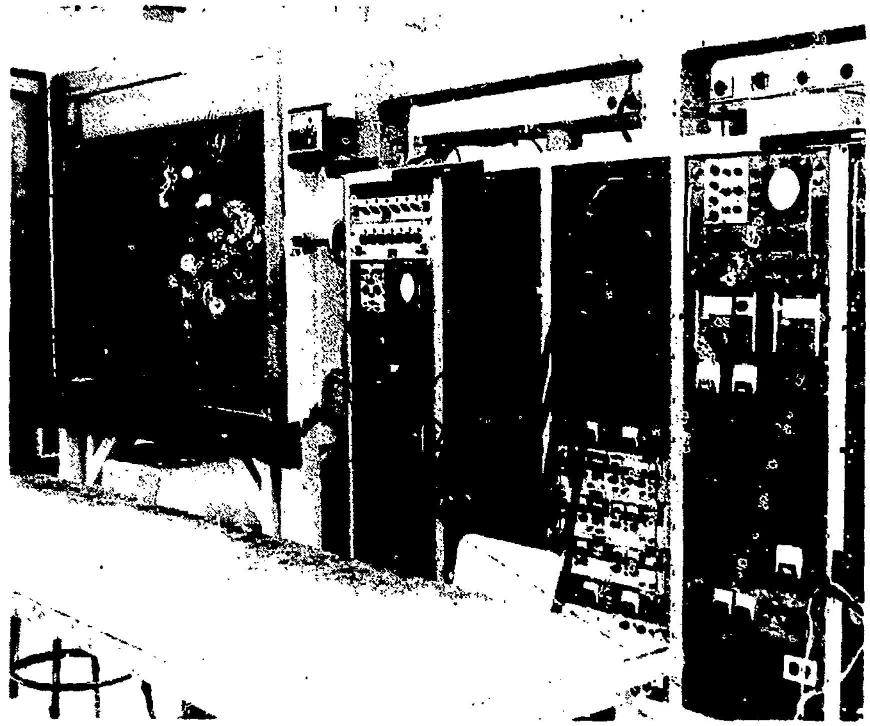


Figure 40. Synchronizer Burn-in Facility, APQ-113

troubleshooting is required. Although the test facility was not intended as a troubleshooting facility, failures did occur which were thermally related and would not occur at ambient temperature. To cope with this problem, special test covers and fixtures were fabricated for the units which would allow test points to be monitored internal to the unit. This provided the ability to isolate problems to a component or group of components.

(4) Equipment Test

The Equipment test (Figure 31), which originated during the APQ-113 development program phase to assure that the LRUs were compatible as an integrated radar, was not changed during the program restructuring, as the emphasis was directed at identifying the problems early in the test flow, well before equipment test. The improvements incorporated at the APQ-120 equipment test level are reported to be based on problems experienced with the performance of delivered equipment.

(5) RAT Test

Approximately 30 percent of the APQ-113 radars were subjected to 130 hours each of reliability acceptance tests (Figure 31) where they were environmentally exposed to temperature extremes and cycling and fixed frequency vibration. On completion of the

RAT test, the radar received a complete functional test. The RAT testing for the APQ-120 is shown as a change to the original program, as it was originally required but not performed.

e. Test Program Effectiveness

The overall upgraded test program structure was designed for optimum cost effective defect screening by emphasizing controls at the beginning of the process, where failure costs are at a minimum, through parts burn-in, 100 percent incoming test and product environmental screening. Described in a failure distribution model (Figure 41) the APQ-113 upgraded test program cumulative screening effectiveness averaged 99 percent as measured from parts screening through Reliability Assurance Test (RAT). The model takes into consideration that Quality/Reliability of delivered radars, with respect to residual defects, is dependent on the quality level of material released to the product flow, the number of workmanship defects introduced during manufacture and the screening effectiveness of each test.

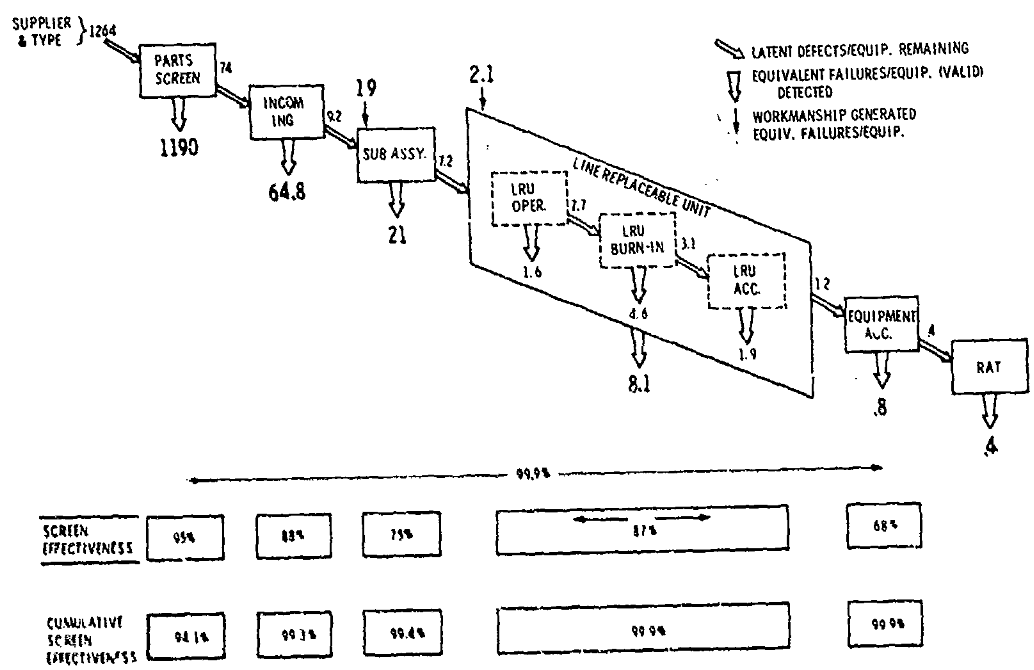


Figure 41. Failure Distribution Model, APQ-113 Test Program Effectiveness

Part failure analysis results, discussed elsewhere in this report, established that 3 of every 10 reported in-process part failures were verified as part screening escapes, or supplier responsibility failures. Factoring this data into the model and converting the program total failures per 1000 parts processed to equivalent failures per equipment

established the level of supplier responsibility part failures entering the process at 1264 failures per equipment. The manufacturing workmanship induced failures were extracted from the same data source and entered in the model at the subassembly and LRU test levels. To simplify the model, the unverified and induced part failures were excluded.

The model shows that Parts Screening was most effective in that 94 percent of the potential part failures per equipment were precipitated, leaving only 74 part failures per equipment to be found. One hundred percent incoming test screening of the high quality parts submitted reduced the quantity of latent part failures per equipment to 9.2 basically establishing incoming test as an 88 percent effective screen. Subassembly manufacturing introduced 19 workmanship defects per equipment into the equipment in addition to the 9.2 part failures per equipment escaping earlier screens. Subassembly test precipitated a conbined total of 21 workmanship and part failures per equipment, allowing 7.2 to escape to the LRU level where an additional 2.1 workmanship defects per equipment were introduced.

The 9.3 failures per equipment introduced at the LRU test were screened at three levels: operational, burn-in, and acceptance test. Burn-in alone accounted for over 50 percent of the LRU test level failures precipitated. The value of burn-in can be further assessed by looking at the 0.4 failure per equipment precipitated during Reliability Assurance Testing, the first equipment environmental exposure subsequent to LRU burn-in. It is shown from this data that the level of failures introduced to RAT would have been approximately ten times higher had burn-in not been performed. This is an indicator of the contribution of factory product environmental screening to initial improvement in performance of fielded equipment, and of the substantial cost leverage available in finding the environmental related failures in the factory as opposed to aircraft flight.

5. FAILURE DISTRIBUTIONS/PERFORMANCE MEASUREMENTS ANALYSIS

This part of the Production Reliability Program subsection examines and analyzes the accumulative APQ-113/114/144 manufacturing test failure data and is organized as follows:

- Program Performance Analysis

    Trends Time Phases
    Early versus Mature Measurements
    Test Level Failure Distributions
    LRU Failure Distributions

- Parts Performance Analysis

    On Receipt Quality
    Parts Screening
    Test Level Comparison

- Product Environmental Screening

    Screening Effectiveness
    Temperature Effect
    Reliability Growth
    Burn-In Failure Distribution
    Screening Value

a. Program Performance Analysis

(1) Trends Time Phased

Equipment performance as measured by average failures per equipment during factory testing improved significantly from initial RDT&E failure levels to downstream equipment production configurations. Figure 42 shows this trend, at just equipment test level, portrayed time phased by equipment program. The chart also shows the initial negative effect on performance of equipment configuration changes for design inherited programs where there is still a high percentage equipment commonality. The initial setback in failure rate for changed production equipment configurations compares with that experienced in reliability qualification testing. The conclusion from this data is that an initial reliability performance penalty is associated with changed equipment, the degree of which is probably a function of the amount of change and the amount of evaluation test performed prior to introducing the change. In the case of the APQ-114, assessed as a 20 percent design change, the initial setback to equipment level test failure rates was approximately 30 percent from the on-going production APQ-113 performance level. This initial failure rate gap steadily decreased with time, as the APQ-114 test performance improved, and the APQ-113 leveled off. The significantly improved starting point for the APQ-114 as compared with the initial APQ-113 is fundamentally due to the high percentage commonality between the two equipments permitting the transfer of the learning.

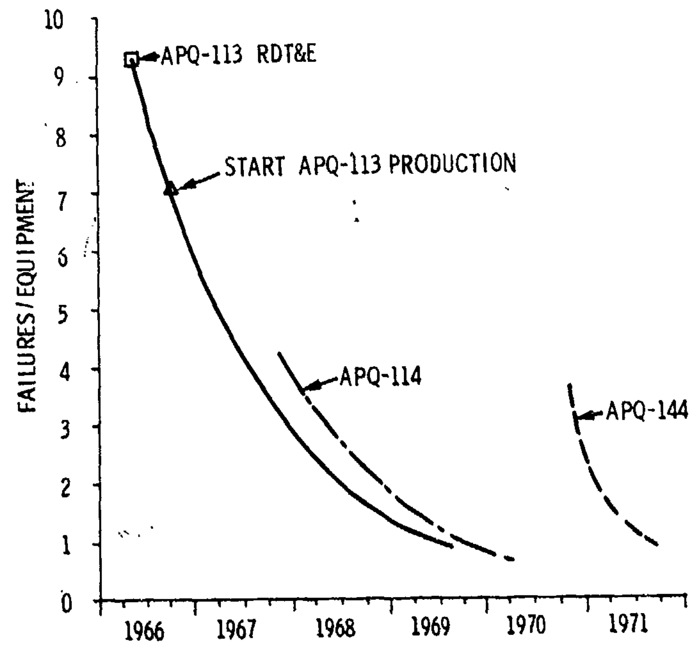


Figure 42. Equipment Test Performance - Factory

The initial APQ-144 test performance, while 15 percent better than the initial APQ-114, still exhibited an increase in failure rate, approximately six times higher than realized on the APQ-114 program, due to the changes introduced and a break in production deliveries. The rate of performance improvement and the levels achieved by all three configurations reflect the effectiveness and timeliness of corrective action in elimination of systematic failures and the increasing difficulty in sustaining corrective action at a constant rate as the failure-free boundary is approached.

(2) Early versus Mature Measurements

Examining portions of the same data in two different program time frames described as "early" versus "mature", to determine the in-process failure trends versus time, provides further insight. Figure 43 describes the average failures per equipment during the first half (early) of the APQ-113 program versus the last half (mature) average of the APQ-114 program and distributes the failures by test level.

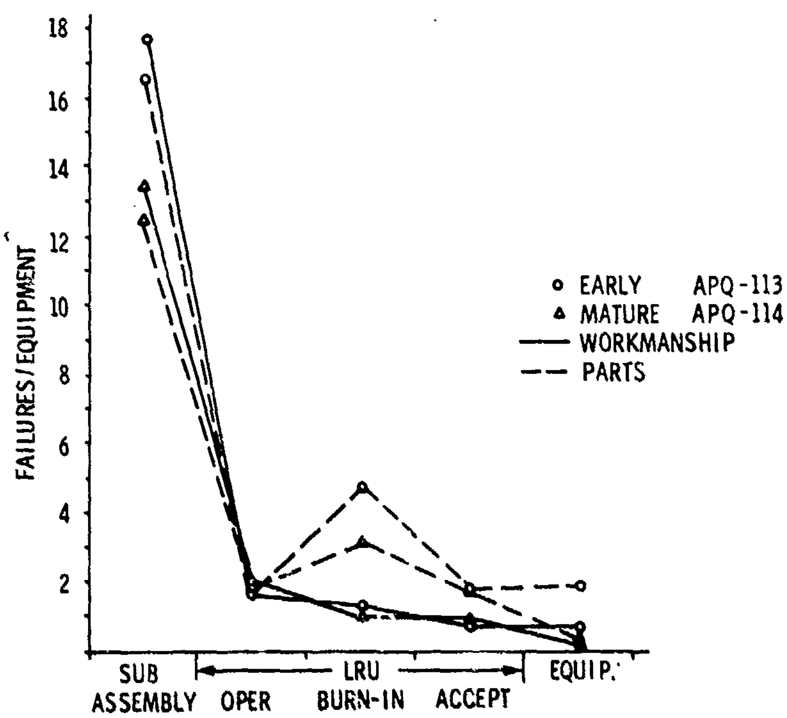


Figure 43. Program Failure Trends

Subassembly test is the only level in the in-process test flow where workmanship failures exceeded part failures. This relative position did not change throughout the program even with the 23 percent average workmanship improvement achieved at subassembly test in the mature phase of the program. Workmanship problems, which are classified as induced, occur at a significantly lower, and ever decreasing rate, at the equipment levels from LRU operational through equipment test.

The mature APQ-114 equipment realized a 70 to 80 percent reduction in workmanship induced problems at the equipment test level, becoming essentially failure-free in this category. There was also a reduction of approximately 28 percent in workmanship failures at LRU burn-in. The evident lack of improvement at the LRU acceptance test for both workmanship and part failures is attributed primarily to the high effectiveness of the burn-in test as a screen from the beginning of the program.

The mature equipment component part failure rate improvement of approximately 25 percent at the subassembly level, Figure 43, parallels the workmanship improvement. The component failure rate improvement at burn-in averaged 33 percent. However, the most significant factor is the effect of the product burn-in screen as a failure precipitator even on environmentally screened component parts as is shown by the sharp rise in the part-related problems at burn-in. The number of part failures precipitated at burn-in is approximately 45 percent of the failures precipitated at all LRU test levels. Dimensioning this precisely is difficult due to burn-in induced failures being detected and reported as having occurred at LRU acceptance test. Based on this data, it is concluded that without product environmental screening only one-half of the potential failures would be found through equivalent level ambient testing.

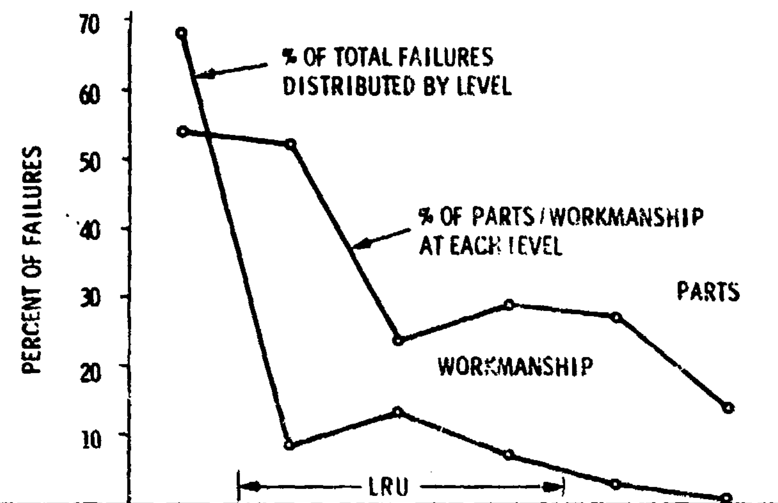
Another observation is that, even with the reduction in part related failures at burn-in in the last half (mature) of the APQ-114 program, burn-in continued to be an effective screen.

At the LRU operational test level, the workmanship to part failure ratio was nearly one-to-one throughout the program. This is attributed to the limited operational test being a low discriminator for part problems, but finding the obvious workmanship problems which is fundamentally what it was established to do.

(3) Test Level Failure Distributions

An analysis of all the factory in-process test failures (Figure 44) on the APQ-113 through APQ-114 showed that nearly 70 percent occurred at the subassembly test level. The subassembly failures were almost equally divided between workmanship and parts related problems with workmanship problems being slightly higher. As the cost of finding and correcting failures at this level runs one-third the cost at the LRU and one-fifth at the equipment level, it emphasizes the value of structuring a test program to include comprehensive subassembly testing. This chart also shows the decreasing incidence of workmanship problems with progressive test levels, until parts related problems become predominant, reaching the 85 percent level by reliability acceptance testing.

Looking at the in-process failure data, with subassembly failures included, is necessary for an overview but tends to overshadow the equipment level failure trends due to the front end weighting. Figure 45 displays the APQ-113, -114 and -144 data excluding subassembly failures for analysis purposes. The impact of LRU burn-in on equipment level testing is clearly evident as LRU burn-in accounted for 40 percent of all equipment level failures. The distribution of part related failures to all failures at each test level is also shown. The overall trend to 85 percent part failures in reliability acceptance testing is the result of the progressive elimination of workmanship failures with increasing test levels. In both levels of temperature testing, LRU burn-in and RAT, the percentage of part failures relative to workmanship significantly increase.



TEST LEVEL		S/A	OPER	BURN-IN	ACCEPT	EQUIP.	RAT
AVERAGE FAILURE COST $	1969	53		154		297	264
	1972	73		180		360	317

Figure 44. In-Process Test Failure Distribution, APQ-113/114/144

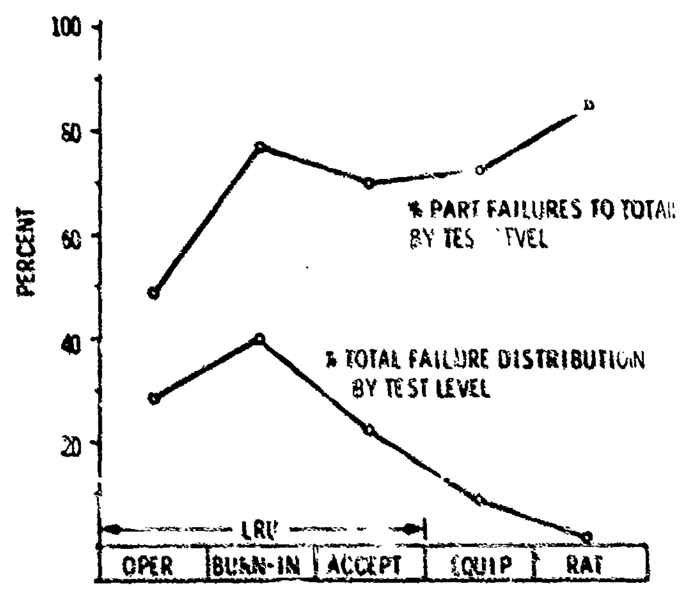


Figure 45. Test Level Failure Distribution, APQ-113/114/144

(4) LRU Failure Distributions

The distribution of factory in-process test failures by LRU over the APQ-113, -114 and -144 programs is displayed in Figure 46 which shows for each equipment level of test the percent of total problems experienced by each LRU. The initial observation is that the apportionment of failures by LRU follows the complexity pattern established by LRU parts count as the RTM, which has about 30 percent of the radar's parts, accounted for about 32 percent of the problems, while the ACU, having about 13 percent of the parts, also experienced an average of 13 percent of the problems. The Synchronizer and Indicator/Recorder LRUs departed significantly from this pattern. The Synchronizer experienced only about one-half of the problems expected on this basis, while the Indicator/Recorder experienced twice as many.

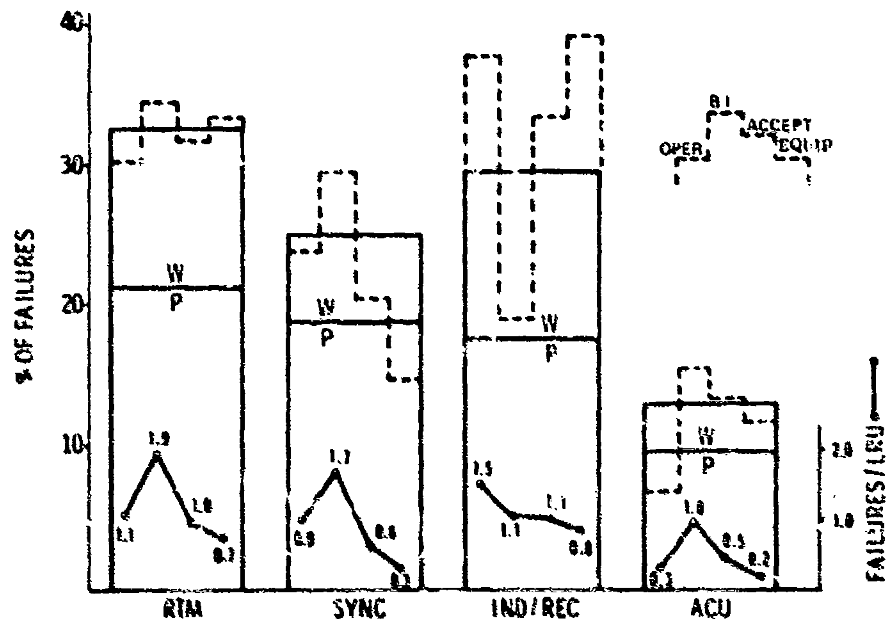


Figure 46. Part and Workmanship Failures, APQ-113/114/144

The better than expected Synchronizer performance can be accounted for, based on its digital integrated circuit design and regimented printed wiring assembly packaging configuration. Further support to this effect is provided by the low workmanship to part failure ratio as compared with the other LRUs. Most of the Synchronizer workmanship problems were identified and corrected at board test at subassembly level. Conversely, the Indicator/Recorder entered LRU level test with a high proportion of chassis mounted parts not tested at the subassembly level.

Figure 46 shows how the approximately 40% environmentally precipitated failures were distributed by LRU over the entire APQ-113/114/144 programs. Details of the APQ-144 data alone are discussed later in relationship to Figure 47. Although the Synchronizer was second to the RTM in burn-in failures per LRU, the Synchronizer was

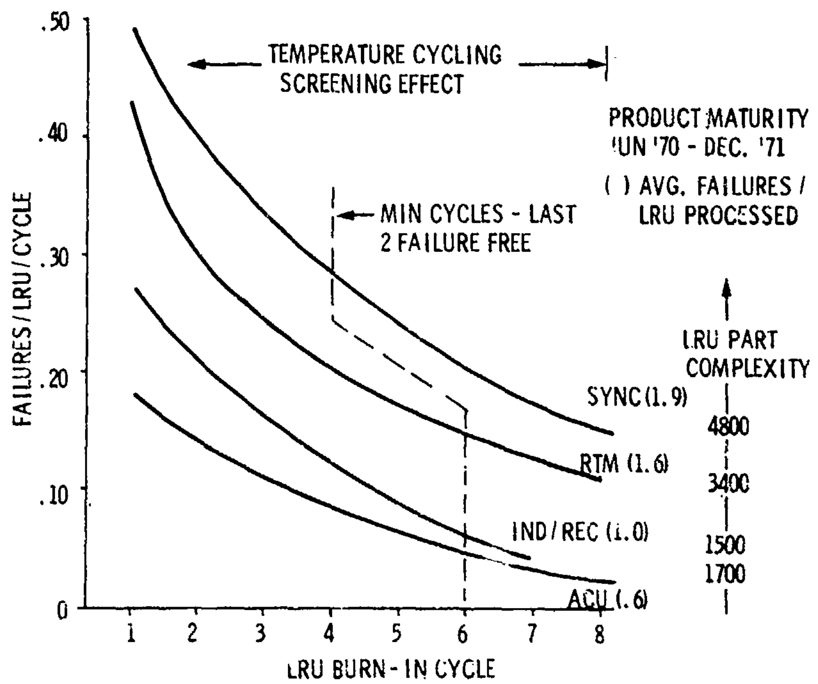


Figure 47. APQ-144 LRU Burn-in Failure Distribution

subjected to a minimum of four cycles while the other LRUs all were exposed to a minimum of six. The Indicator/Recorder failure trends by test level vary from the other LRUs at operational and burn-in testing. The higher failure rate at operational test is attributed to the chassis mounted components, untested at subassembly level, and the low level of failures reported at burn-in is because of the limited availability of test points for this LRU in the environmental test chamber. As a result, the Indicator/Recorder burn-in precipitated failures were detected and reported at the LRU acceptance test level.

Extending the LRU failure distribution comparison to include the reliability test (RAT), as well as the platform and field experience, provides the picture shown in Figure 48. The additional data from these test or field experience levels closely corresponds with the factory experience, the conclusion being that problem distribution by LRU, as experienced in the factory, is essentially the same distribution in the field and may therefore be used as a valid predictor of relative field performance.

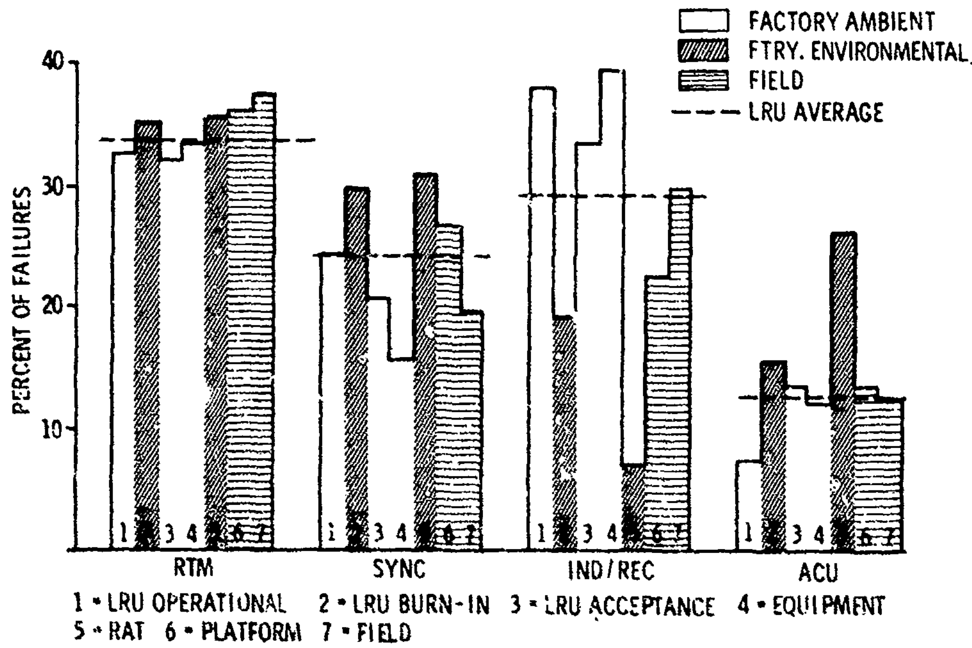


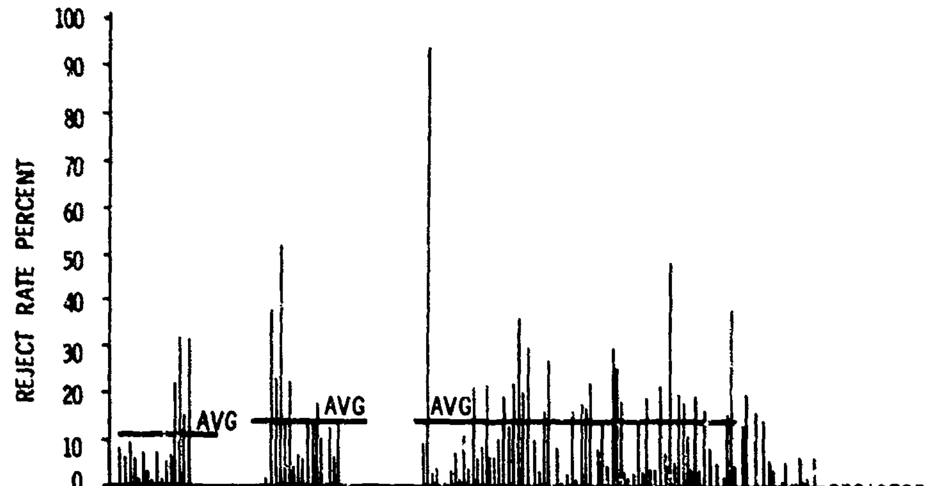
Figure 48. Progressive LRU Performance, APQ-113/114/144

b. Parts Performance Analysis

(1) On-Receipt Quality

Figure 49 uses supplier data to illustrate the lot-to-lot variation in screening reject rate experienced by the supplier. Lot-to-lot variation is expected when it represents the first screening of a production lot. However, a similar degree of variation is observed at Incoming Test after completion of supplier screening. Lot-to-lot quality variation is typically experienced at Incoming on 100% screened material as Figure 50 illustrates, which supports the need for Incoming Test control even on screened material.

Data collected from 1968 through 1971 and displayed in Figure 51 shows screened versus nonscreened material rejection rates, based on Incoming ambient test measurements. The 5:1 average improvement factor is an early indicator of the improved lot quality of screened material which is attributable to the additional supplier testing, resulting in removal of defective parts from the lot population. This ratio is not a measure of the value of screening, as the true value cannot be determined through ambient incoming testing. However, it does establish the difference in the level of on-receipt problems that can be expected between screened and nonscreened material.



PEAK/VALLEY RATIO	DIODE	TRANSISTOR	INTEGRATED CIRCUIT	RESISTOR	CAPACITOR	
	33:1	53:1	94:1	30:1	10:1	1968 - 69
	50:1	12:1	14:1	28:1	5:1	1970
	14:1	36:1	5:1	22:1	6:1	1971

Figure 49. Component Screening Lot-to-Lot Variation

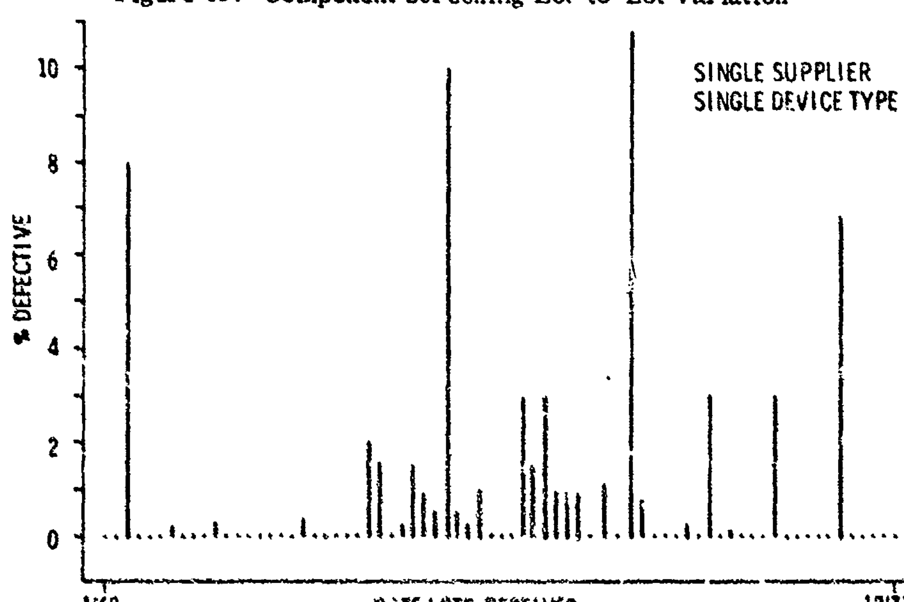


Figure 50. Incoming Lot-to-Lot Quality Variations - Screened Transistors

QTY PARTS TESTED	1968 1,497,000		1969 862,000		1970 785,900		1971 798,000	
	REJ. RATE		REJ. RATE		REJ. RATE		REJ. RATE	
PART TYPE	SCREENED / NON SCREENED	APPROX. K FACTOR	SCREENED / NON SCREENED	APPROX K FACTOR	SCREENED / NON SCREENED	APPROX K FACTOR	SCREENED / NON SCREENED	APPROX. K FACTOR
SEMICONDUCTORS	0.2 / 1.1	6	0.2 / 1.4	7	0.3 / 0.9	3	0.15 / 0.43	3
MICROCIRCUITS	3.2 / -	NA	2.8 / -	NA	1.5 / -	NA	2.3 / -	NA
RESISTORS	0.1 / 0.6	6	0.1 / 0.2	2	0.2 / 0.2	1	0.1 / 0.1	1
CAPACITORS	0.2 / 0.6	3	0.4 / 0.6	2	0.2 / 0.6	3	0.1 / 0.8	8
INDUCTORS	0.4 / 1.9	5	0.3 / 2.7	9	0.7 / 3.3	5	0.2 / 1.5	8
AVERAGE (EXCLUDING MICROCIRCUITS)	0.2 / 0.9	5	0.2 / 0.9	5	0.2 / 0.7	4	0.1 / 0.5	5

K = IMPROVEMENT FACTOR

Figure 51. Incoming Test Performance, Screened versus Nonscreened

(2) Parts Screening

Comparing the data results presented on Figure 51 and Table XV shows that parts screening precipitated an average of 11% failures while incoming ambient testing of nonscreened material, in the same calendar time period, precipitated less than 1%. This data comparison establishes that the quality of environmentally screened material entering the manufacturing process was, on the average, an order of magitude improved over the nonscreened. It cannot be concluded that all of the screening precipitated failures would have subsequently failed at higher level tests or that parts screening is 100% effective, as even screened material fails at measurable rates throughout the equipment level testing program.

The immediate benefits of parts screening are found in the reduced equipment manufacturing failure costs, and in initially improved equipment MTBF performance achieved through the reduction in infant mortality failures.

While parts screening's immediate advantage is in the elimination of infant mortality failures, the long term contribution to equipment MTBF performance lies in the identification of pattern part problems for corrective action. For standard parts, the failure rate advantage resulting from elimination of a pattern problem will be short term and initially only with the screened version, since the improvement made and factored into the part design or process will apply equally to the unscreened standard part. The same advantage, however, does not extend to comparisons between screened and nonscreened, nonstandard parts and specialty items, because the corrective action is most probably uniquely, and only applicable, to the screened version. These factors need to be considered in accounting for MTBF performance differences of mature equipments which had different complements of screened material when manufactured.

(3) Test Level Comparison

Figure 52 traces the performance of the APQ-113, -114 and -144 electrical components, specialty items, and major procurement items from the parts screening level through equipment reliability testing. Because of the overlapping of the performance trend lines for integrated circuits, transistors, diodes, capacitors, and inductive devices, the area representing their performance has been shown shaded in. Resistors because of a significantly better than average failure rate, are shown separately. Specialty devices and major procurement items are also shown separately because of higher failure rates. One of the key points of this chart is the orders of magnitude improvement in part failure rates in going from test level to test level during processing. This may also be described by pointing out that the part failure rates in reliability testing are on the average ten times better than measured during in-process factory testing and the failure rate experience in factory testing and incoming is on the average ten times better than the part screening failure rates. This relationship established a rule of thumb for parts performance improvement from parts screening to factory to reliability testing of a factor of 10 for each level. If the major procurement item performance were normalized by part complexity, their parts failure rates would fall within the chart's shaded area. However, the MPI performance is a unique problem discussed in another section of this report.

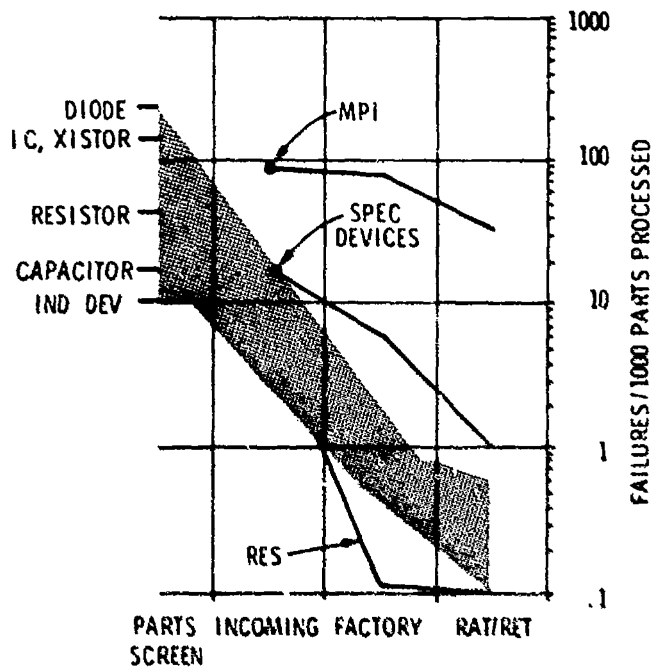


Figure 52. Progressive Parts Performance. APQ-113, 114, 144

c. Product Environmental Screening

Analyzing the APQ-144 burn-in data shows the screening effect of temperature cycling, per cycle of exposure, on failure precipitation for each of the electronic LRUs of the radar (Figure 47). The data shown for the APQ-144 equipment is considered to be

representative of mature product burn-in experience because over 400 LRUs of each type had been previously bruned in, even though functional and configuration changes had been incorporated in going from the APQ-113 to the APQ-144. The curves indicate a relationship between failures and LRU complexity, measured by parts count, as the failures experienced per cycle generally increased with the LRU's parts complexity.

Environmental screening of complex avionics equipment, for even mature products, is effective, as demonstrated by the average of approximately two failures per APQ-144 Synchronizer processed, that were precipitated within only four environmental cycles. Similar, but somewhat fewer, failures were screened out of the other less complex LRUs.

(1) Screening Effectiveness

Figure 53 is a measure of temperature screening effectiveness and again on mature equipment. It depicts on a cumulative basis, by burn-in cycle, the percent of LRUs processed which failed. Since only the initial failure of the LRU was counted, and in the cycle in which the failure occurred, the end points equal the percentage of the LRUs processed which failed during temperature screening. In the case of the Synchronizer, the curve shows that over 80 percent had failed at least once, by the fourth environmental cycle. It also means that only 20 percent of the Synchronizers went through temperature cycling failure-free. The number at the end of the curve represents the average number of failures occurring on each failed LRU. The data shows that on the average, Synchronizers failing burn-in experienced over two failures each. Slightly over 40 percent of the less complex ACUs failed, averaging 1.5 failures each.

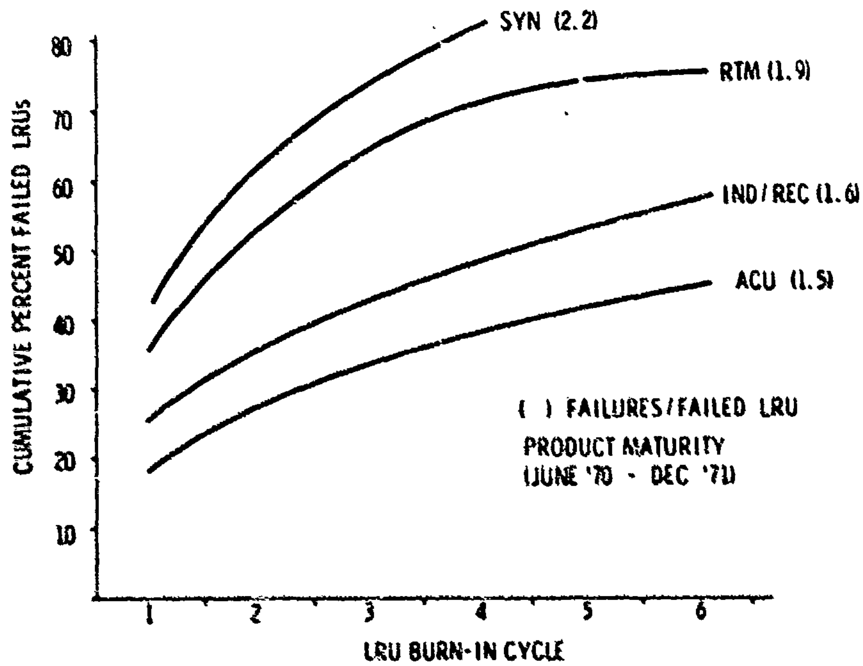


Figure 53. LRU Burn-in Screening Effectiveness, APQ-144

Significantly, of all the LRUs that failed, approximately one-half failed in the first temperature cycle.

(2) Temperature Effect

The effect of temperature environment on failure precipitation, for the temperature profile utilized, is reflected in Figure 54 establishing that over two-thirds of all LRU burn-in failures were observed at low temperature. The significance of this experience is that if it were not for this factory product environmental screening, the preponderance of these burn-in precipitated failures would have occurred when the equipment was installed in the aircraft and subjected to flight environments. On the APQ-113, -114, and -144 some of the failures would have occurred during the reliability acceptance sample test.

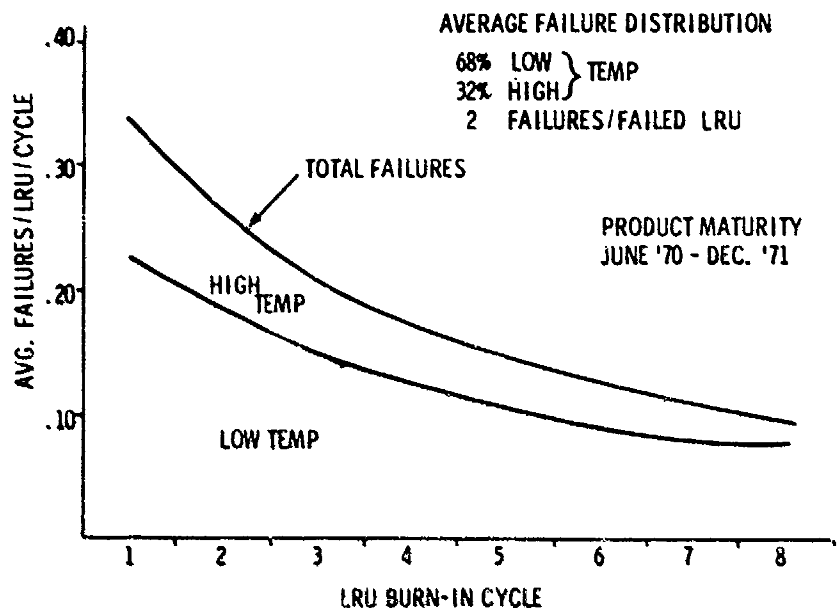


Figure 54. Product Environmental Screening - Temperature Effect, APQ-144

(3) Reliability Growth

Assuming that the only value of 100 percent product environmental screening is the identification and removal of infant mortality failures, the effect of not performing the screening would be of just transferring the cost and responsibility for finding and fixing those problems to the customer at platform and field levels, at considerably greater expense. Furthermore, under this assumption, most of these initial failures would occur and be corrected in the first hundred hours of equipment operation under flight conditions, and would not negatively bias long term equipment MTBF performance measurements.

However, the real value of product environmental screening is in contribution to reliability growth through identification and correction of pattern problems. Figure 55 shows the initial LRU burn-in experience for APQ-113 equipment in 1966 and 1967 as

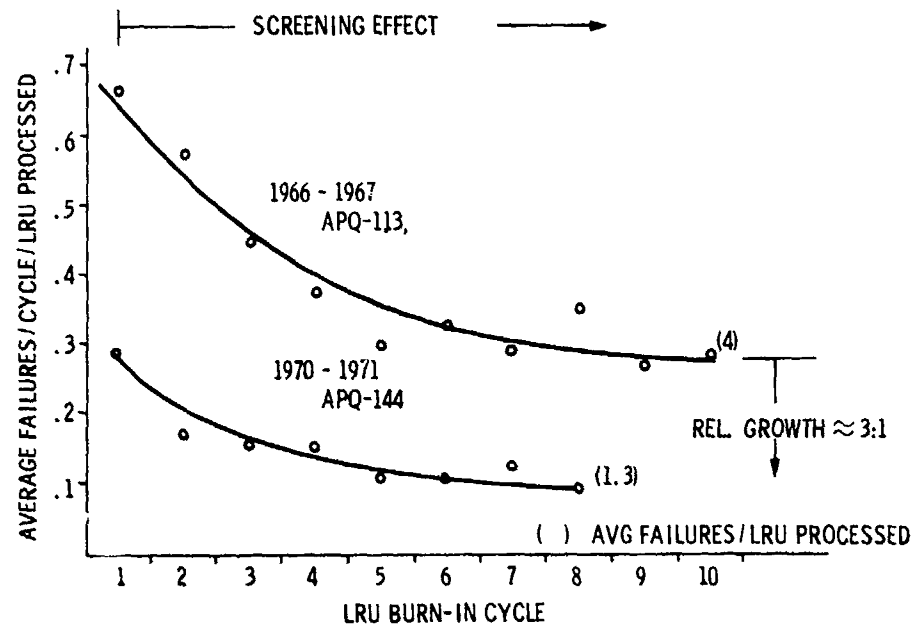


Figure 55. Product Environmental Screening - Initial APQ-113/Mature APQ-144

compared with the 1970-71 experience with the APQ-144. The screening effect of temperature cycling can best be described by the improvement in failure rate with increasing temperature cycles by removal of infant failures. If this were all that occurred, then it would be expected that the APQ-144 curve would overlay the APQ-113. The fact that it does not makes it clearly evident that a significant reduction in failures was achieved. This reduction is attributed to an aggressive reliability program addressing all burn-in failures. It is also further evidence that burn-in precipitated failures are not solely of the "infant mortality variety" but are comprised of pattern failures with distinct failure rates which are correctable. On the initial APQ-113 equipment, the average failures per LRU processed were 4 and leveled out at 0.3 after exposure to a minimum of ten temperature cycles. The APQ-144 equipment, three years later, averaged 1.3 failures per LRU and through a minimum of six temperature cycles exited burn-in at an average of 0.1 failure per LRU processed. This is a measured product performance improvement of 3:1 under environmental conditions.

(4) Burn-In Failure Distribution

Figure 56 further breaks down the failures experienced at the LRU burn-in test level for the APQ-113, -114 and -144. The category described as parts failures and discussed elsewhere in this section actually included both major procurement items and specialty devices.

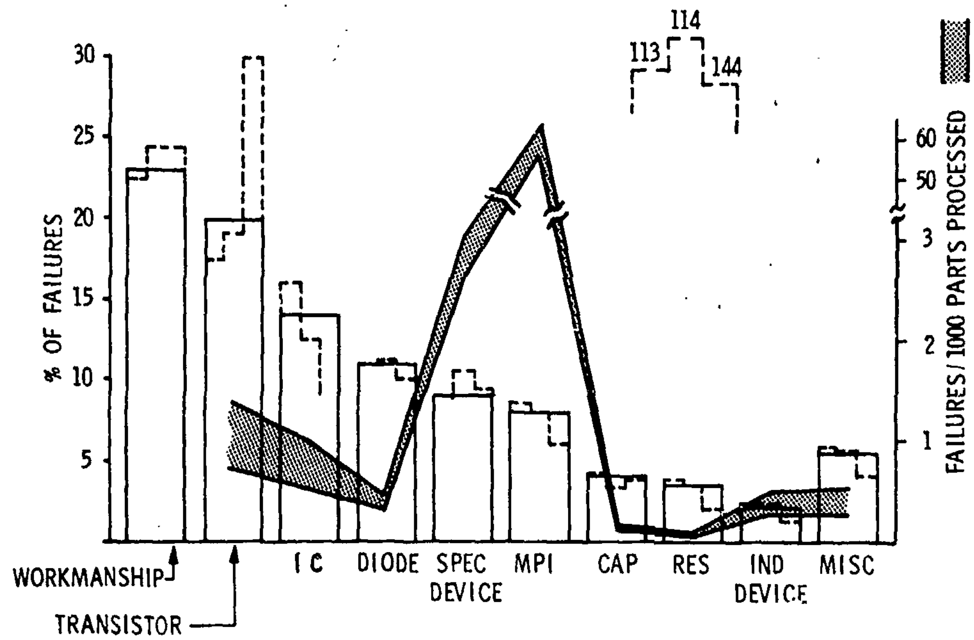


Figure 56. LRU Burn-in Failures - Parts and Workmanship, APQ-113/114/144

Major procurement items and specialty devices together accounted for over 20 percent of the total problems experienced in burn-in test. When these items are related to a failure rate base of failures per 1000 parts processed, it can be seen that they fail at average rates ranging from 5 to 100 times the failure rates of electronic components. This comparison is made both to highlight the necessity for the procurement control of these items, and to stress the impact of these items on system reliability performance. Discussion of the major procurement items is covered in another section of this report.

(5) Screening Value

As shown on other charts, the major achieved improvement was in parts related performance, primarily because, on the average, parts, Major Procurement Items and Specialty Devices accounted for almost 80 percent of the burn-in failures.

The value of 100 percent product environmental screening during factory processing can be summarized as follows:

1) It is the most cost-effective means to precipitate and remove from individual product those infant mortality failures which occur only under environmental stress.

2) The long term reliability worth is in identifying for corrective action those design, material, and process pattern problems which, if uncorrected, will continue to constrain equipment MTBF performance under intended use environments.

6. PROBLEM IDENTIFICATION AND ANALYSIS

This part of the Production Reliability Program subsection describes the problem identification and corrective action methods and experience forming an integral part of the APQ-113/114/144 radar reliability program. The subject material covered is outlined for presentation in two primary areas as follows:

- Part Failure Analysis

  Unverified Failures
  Supplier Responsibility
  System Test Failures
  Failure Analysis Leverage
  Scope of Analysis
  Corrective Action

- Technical Problem Solving Routines

  Reliability Engineering
  Quality Assurance
  Design Engineering

The part failure analysis portion contains an analysis of the summarized data results obtained from laboratory part failure analysis records generated through-out the radar production program.

The technical problem solving routines identified and discussed consist of those management data reporting and corrective action practices and procedures proven effective in identifying, highlighting, dimensioning, and communicating design, material, and workmanship problems.

a. Part Failure Analysis

The APQ-113 Reliability Corrective Action Program relied extensively on piece part failure analysis. The contribution of the failure analysis activity was in identifying and separating problems from nonproblems, diagnosing the root cause of the real problems, and providing analysis findings in a timely manner through an in-house laboratory facility.

(1) Unverified Failures

Data obtained throughout this program substantiates the need to verify the initial diagnosis, troubleshooting, and replacement action taken by trained factory technicians. Typically 30% of the parts reported as factory failures and submitted for failure analysis, even when screened by quality and reliability engineers, could not be verified as failures through laboratory analysis (Figure 57).

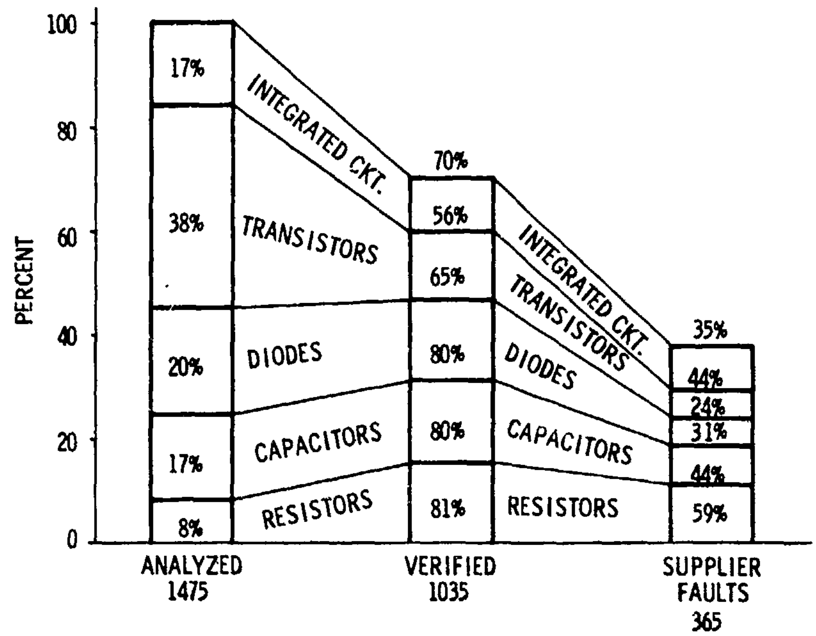


Figure 57. Failure Analysis Experience, APQ-113/114/144

(2) Supplier Responsibility

The 70% of the part failures that were verified were subjected to further examination, measurement, and dissection to the extent necessary to determine the cause and responsibility for the failure. On the APQ-113 Program, utilizing 90% environmentally screened material, an average of only 35% of the verified piece part failures could be attributed to part supplier responsibility caused by either faulty workmanship, process, or design. The remaining 65% were attributed to an internal responsibility where the failure had been induced through testing, troubleshooting, assembly and, in some instances misapplication.

(3) Equipment Test Failures

Figure 58 looks at equipment level test failures and failure analysis results across the entire APQ-113/114/144 programs. The bars on the chart show the failure distribution of the identified parts as a percent of total part failures experienced. (Note: This data is normalized to part usage on other charts.) The line identified as "analyzed" shows the high interest (80%-90%) in analyzing semiconductor part failures over the entire program. It also shows that the verification rate for ICs and transistors was as low as 50% to 60%. This points out that complex parts are more apt to have subtle variations detectable only in the circuit application, and are even more likely in troubleshooting to be mistakenly identified as the cause of the problem. The third line on the chart shows the percentage that is supplier responsibility as determined from the failure

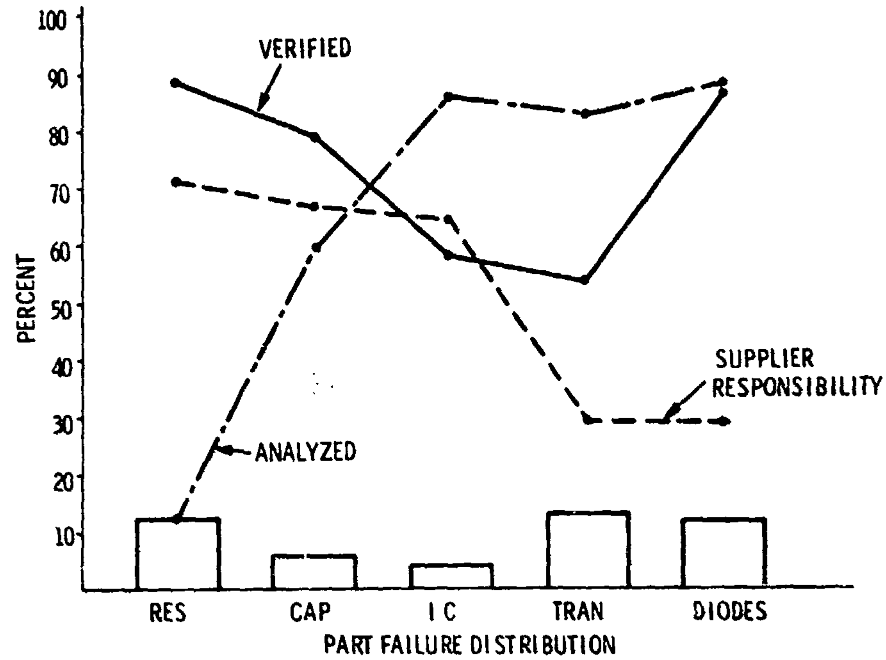


Figure 58. Equipment Test Part Failures, APQ-113/114/144

analysis. The supplier responsibility chart line is shown as a percent of just the verified failures which means that the balance of the verified failures are due to some externally induced cause. Resistors and capacitors, because of relative simplicity, have readily discernible supplier responsible failure causes, while transistors and diodes appear to be more susceptible, in application, to external failure causal influences.

Conducting extensive failure analysis at the equipment test level is considered particularly important because the problems occurring and the knowledge gained are more closely related to fielded equipment experience. From the results of laboratory failure analysis reports obtained from factory equipment test reported failures, field part replacements also need to be analyzed to correctly assess problems and to accurately dimension equipment MTBF performance.

These findings emphasize the need for analysis and point out the potential erroneous conclusions and ineffectiveness of a corrective action program based on utilization of "raw" failure data. Also, performance measurement of an equipment such as MTBF would be unrealistically low if the only basis for assessment was uncensored part failure data. This conclusion is attributed to the unverified part failure percentage of 30% compounded with the associated number of induced part failures experienced even under controlled factory test conditions.

(4) Failure Analysis Leverage

Failure analysis and corrective action has its greatest leverage and impact on equipment reliability growth and performance when conducted early in a program's evaluation test and initial production phases. The APQ-113/114/144 experience (Figure 59) showed that in the first half of the program an average of over 60% of the LRU and equipment level failures were selected for laboratory failure analysis. This rate dropped to an average of 25% for the last half of the program. The early emphasis is essential as this period is when a higher percentage of part misapplication problems are uncovered, as well as inherent piece part design and process deficiencies. However, failure analysis activity must be sustained throughout a program due to variations in part quality and particularly due to unapproved subtle part configuration changes or improvements introduced by suppliers.

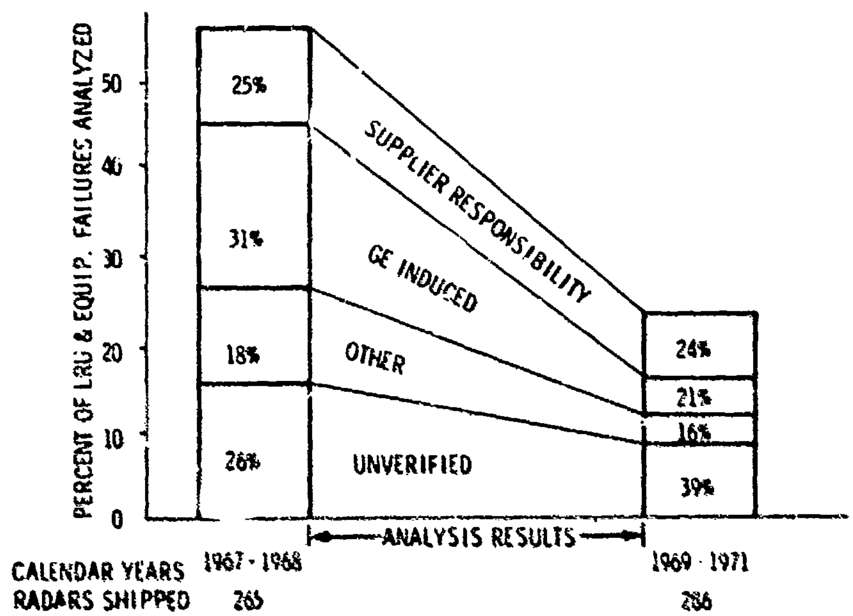


Figure 59. Failure Analysis Trend, APQ-113/114/144

Concentration on the higher test levels was more effective because of the test screen funnel effect where the higher level failures were less influenced by both internal workmanship and induced causes. Failures escaping lower level screens are more apt to be long term reliability problems which would eventually constrain fielded equipment MTBF performance if not corrected. These "escape" failures were also of paramount interest in measuring effectiveness of screening and in determining necessary adjustments to in-place screens.

(5) Scope of Analysis

The scope of analysis conducted is described in Table XVI by part class. The actual number of steps varied with each failed part because the analysis was terminated as soon as the failure cause was determined.

TABLE XVI. FAILURE ANALYSIS FLOW

FLOW / DEVICE	EXTERNAL EXAMINATION	FINE & GROSS LEAK TEST	MECHANICAL MEASUREMENT	X-RAY	ELECTRICAL MEASUREMENT – TEMPERATURE: RM	ELECTRICAL MEASUREMENT – TEMPERATURE: HI	ELECTRICAL MEASUREMENT – TEMPERATURE: LO	INTERNAL VISUAL	ELECTRICAL PROBE	CROSS SECTION	SEM	SEM MICRO PROBE	PHOTOGRAPHY	REPORT
SEMICONDUCTORS	■	■	■	■	■	■	■	■	■	■	■	■	■	■
RESISTORS	■		■	■	■	■	■			■			■	■
CAPACITORS	■		■	■	■	■	■			■			■	■
INDUCTORS	■		■	■	■	■	■			■			■	■
ELECTRO-MECHANICAL	■		■	■	■	■	■			■			■	■
CIRCUIT INTERRUPTING DEVICES	■			■	■	■	■	■						

■ ANALYSIS PROCEDURES USED BY DEVICE TYPE

□ NOT USED

The availability of an in-house laboratory equipped and manned to perform this work was a factor that favorably influenced the corrective action time cycles. This was evident in the reliability qualification test programs where measured reliability growth rate was dependent on the cycle time from recognition of a systematic problem to incorporation of the corrective action. While dependent on many variables, the average turnaround time for a failure analysis using the in-house capability was between one and two weeks. With expedited priority, the same analysis could be completed in one day or less.

Failure analysis contribution to reliability growth can be enhanced through careful management of the selection processes of failed parts. High potential candidates for analysis are those parts which fail out of proportion to their application frequency. This type of data was available on the APQ-113 program through the quality control test and inspection data system and the Reliability Engineering Severity Factor Listing discussed in another part of the study.

(6) Corrective Action

Failure analysis alone only identifies the causes of problems; therefore corrective action is essential if progress in terms of reliability growth is to be realized. On the APQ-113 program, the results of the part failure analyses were given to suppliers with requests to confirm them and to respond relative to corrective action implemented. In looking back on many programs and assessing effectiveness of this activity, it has been found that approximately 40% to 50% of the supplier faults diagnosed were either eliminated or significantly reduced. The fact that corrective action, even when implemented, is not 100% effective in every case, is further justification in support of recurring part and product environmental screening.

b. Technical Problem Solving Routines

The success of an equipment reliability program is measured in terms of reliability growth and achievement which is in direct proportion to the timely identification and correction of equipment problems. The cycle of problem identification, evaluation, and corrective action is continuous and must be diligently performed during all evaluation and production phases, each step in the cycle being critical to the attainment of maximum equipment reliability growth and optimum field performance.

Probably as many different approaches exist for solving technical problems as there are reliability and quality engineering organizations. The common denominator that distinguishes the successful routine from the unsuccessful falls in the area of effectiveness of execution and the degree of attention to detail applied to make the routine work. The fundamental characteristics that contributed to the successful APQ-113 problem solving routines were simplicity, identified responsibility for solution, periodic measurements of progress, test validation of corrective action, and visible status reporting, providing cross functional communication of the problem nature, input, and solution.

Exception reporting also contributed to effective problem solving. Test and Inspection computer-summarized data was arranged so as to highlight high frequency of occurrence problem areas. It was recognized that all program problems eventually had to be solved; but by addressing the high frequency, major impact problems first, whether they were design, material, or workmanship, permitted effective utilization of the technical manpower resources available.

Another key to successful problem solving is early recognition of problems at the lowest possible level of inspection or test, as the sooner a problem can be identified and resolved, the faster the rate of equipment reliability growth. APQ-113 data systems provided extensive visibility at all levels of assembly and reports were generated to both scope the severity of the problem and to display it for Action Reports. In addition, all routines defined responsibility for corrective action and contained feedback loops which would ensure that the problem had been resolved.

Chosen for detail review are the following problem solving systems and routines which were considered instrumental to the APQ-113 Attack Radar's reliability growth. They by no means represent all routines that were used or were available for use; however, each one satisfied part or all of the basic criteria for effective Problem Solving.

- Reliability

  Reliability Action Items
  Severity Factor Listing
  Pattern Failure Summary
  Failure Analysis Routines

- Quality Assurance

  Problem Book
  Quality Reports
  Manufacturing Operator Report

- Design Engineering

Problem Correction Plan

(1) Reliability Engineering

(a) Reliability Action Items - The Reliability Action Item System provided for resolution of problems that were primarily design or material oriented. The Radar Reliability organization, being responsible for the generation and maintenance of the system, selected each action item after analysis of the Severity Factor Listing, Pattern Failure Summary, Failure Analysis Reports, and/or Reliability Test Program Reports.

When analysis revealed a pattern problem, the Reliability Project Engineer initiated an integrated plan, formally described as an Action Item (AI), (Figure 60), which delineated the problem, listed pertinent reference data and identified the engineer responsible.

The designated Reliability Engineer pursued the problem resolution and maintained a complete, current log of activities detailing all data acquired during investigation. Each week progress was reviewed with the Project Engineer and the plan was updated or revised as necessary.

Corrective action resulting from the problem investigation and analysis was continually evaluated until concrete evidence established that the problem was corrected and the Action Item could be closed.

(b) Severity Factor Listing - The Severity Factor Listing highlighted in-process pattern failures of component parts found during electrical test. The report normalized part usage versus failure frequency, thereby assuring that high failure rates of low usage parts were not masked by moderate failure rates of high usage parts which is possible if only failure frequency criteria were applied. A minimum of five failures per year of the same component part was established as the threshold for inclusion in this report.

To dimension the relative effect of a problem on the radar, a "Severity Factor" rating was established. The base for this rating was the RN60 resistor selected because of its high quantity usage (2500 per radar), its generally homogeneous failure distribution, and its highly reliable performance. All RN60 resistor failure occurrences were strictly monitored and analytically verified because of their impact on all calculations. The severity factors of all failed parts used in the equipment were based on the following equation.

$$SF_{pp} = \frac{Q_{RN60}\ \lambda_{RN60}\ F_{pp}}{Q_{pp}\ \lambda_{pp}\ F_{RN60}}$$

where

SF_{pp} = Relative severity of the problem part

Q_{RN60} = Quantity of RN60s/radar

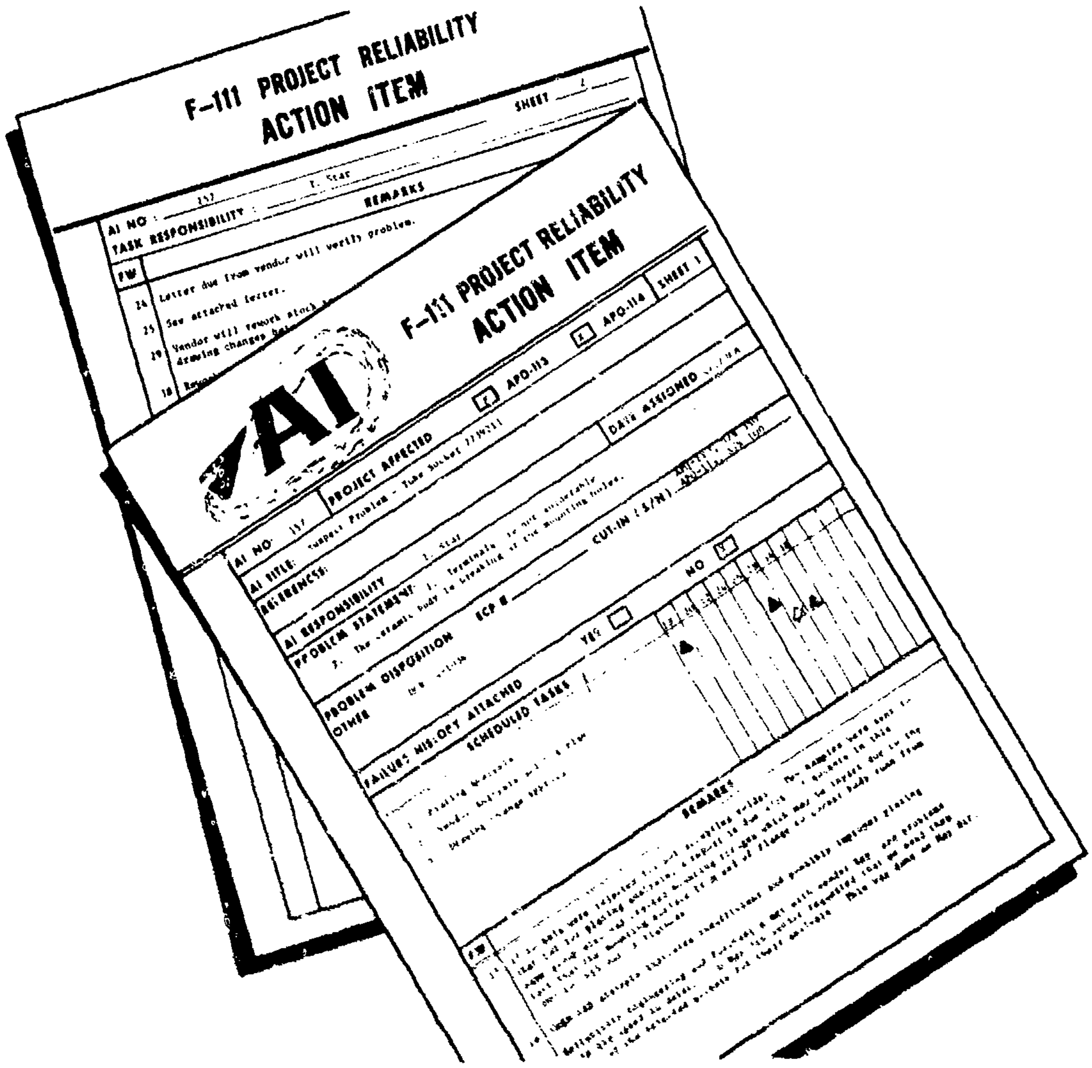


Figure 60. F-111 Project Reliability Action Item

Q_{pp} = Quantity of problem parts/radar

F_{pp} = Quantity of failures of problem part in last 6 months

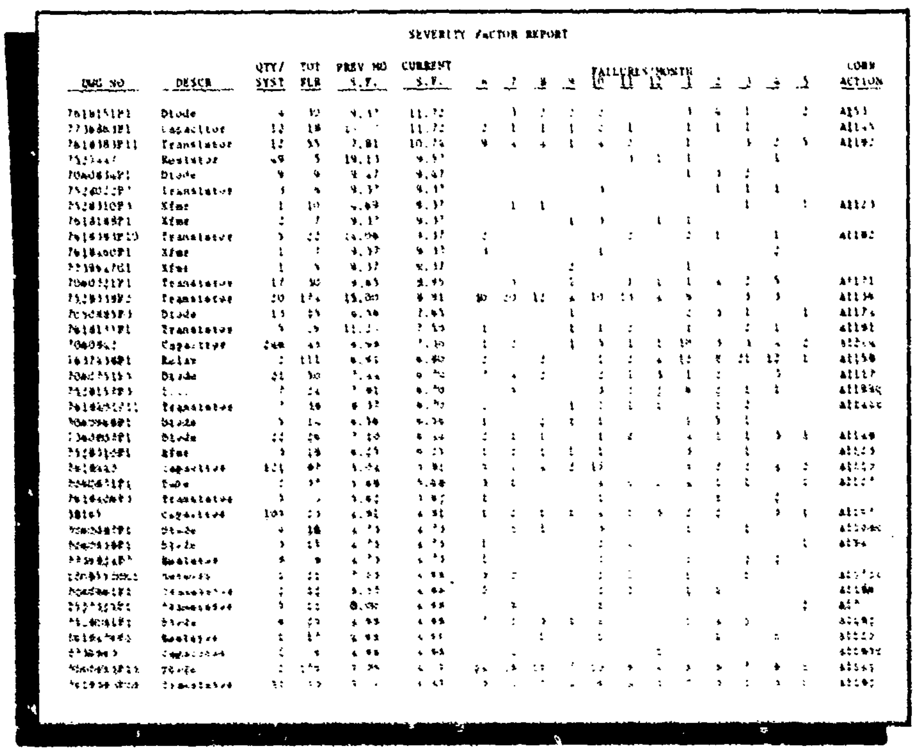
F_{RN60} = Quantity of failures of RN60 in last 6 months

λ_{pp} = Predicted failure rate of problem part

λ_{RN60} = Predicted failure rate of RN60

The equations yields a numerical value that is dimensionless and of no significance when standing alone. Its value is derived from a relative comparison with similar values of other parts. The higher the numerical value, the more divergent the performance in respect to what was predicted, and the more severe its effect on equipment performance. Hence, each part is critically ranked for problem investigation. The RN60 factor modulates the equation in respect to manufacturing fluctuations, since a fairly linear change in failures can be expected with changes in production rates.

To ensure that all major problems were being investigated regardless of severity factor, the report was issued monthly in two formats, the first in drawing number order and the second by severity factor (Figure 61). Using these reports, the Reliability Project Engineer selected problems to include in the Reliability Action Item system. Although severity factor was the major consideration in this section, the monthly failure pattern was also considered. A high incidence of failures led to immediate action, even if the severity factor was relatively small. After final corrective action was instituted, effectiveness was monitored by listing the Action Item number in the "Corr Action" column of the listing and the drawing number was carried for nine additional months.


SEVERITY FACTOR REPORT

DWG NO	DESCR	QTY/ SYST	TOT FLR	PREV MO S.F.	CURRENT S.F.	FAILURES/MONTH	CORR ACTION

Figure 61. Severity Factor Report

(c) Pattern Failure Summary - The Reliability Pattern Failure Summary was utilized to determine frequency of component failures related to specific circuit socket applications. The report supplemented the Severity Factor report by identifying unique part failure patterns that could not be discernible based solely on part failure rates. This computerized report arranged in circuit symbol order, was generated monthly and delineated the cumulative year-to-date failures. A minimum threshold of two occurrences in the previous 12 months was necessary for inclusion in the listing. The format of the report (Figure 62) was designed to give current year part failures by circuit location, and circuit failure performance for previous years. The serial number of the failed assembly/subassembly and test station was also listed to help diagnose if the occurrences were peculiar to one serial number and therefore caused by something other than the part or its application.

PATTERN FAILURE SUMMARY

FAILED PART SYMBOL	FAILED PART DWG NO	SER NO	TST STA	REPORT NO	FISCAL WEEK 2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50	52	CORR ACTION
4A09A05Q2	7618403P9	1968		FLRS					1										1		1										A1193
4A09A05Q2	7618403P9	1969		FLRS																	2				1						
4A09A05Q3	7618403P11	0387	409	645615		X																									Z196
4A09A05Q3	7618403P11	0386	409	645612		X																									A196
4A09A05Q3	7618403P11	0352	410	565537					X																						A196
4A09A05Q3	7618403P11	1969		FLRS												1										1					
4A09A05Q3	7618403P11	1968		FLRS						1											1		1						1		
4A09A05Q4	[illegible]	0387	409	[illegible]		X																									A1192
4A09A05Q4	[illegible]	1968		FLRS												1							1			1					A1192
4A09A05Q4	[illegible]	1969		FLRS													1							1	1				1		
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		X																									A1194
[illegible]	[illegible]	[illegible]		FLRS										2		1									1	1					A1193
[illegible]	[illegible]	[illegible]		FLRS						1	1				1			2						2						1	
[illegible]	[illegible]	[illegible]		FLRS					1						1				1		1			1			1	1			A1192
[illegible]	[illegible]	[illegible]		FLRS		1										1					1							1			A1193
[illegible]	[illegible]	[illegible]		FLRS										1																	

Figure 62. Pattern Failure Summary

Once identified, prioritized, and investigated, the status of each problem was monitored and progress measured through the Action Item System previously described. When positive corrective action was implemented, the Action Item identification number was entered on the report in the "Corr Action" column. A measure of the Corrective Action effectiveness was made with each published listing of the report by reviewing whether a reduction in failure occurrence had been realized.

(d) Failure Analysis Routines - The Severity Factor Listing, Pattern Failure Summary, and Reliability test data were also used to compile and identify problem parts that required laboratory failure analysis. Candidate parts were listed twice, in drawing number sequence and, by reference designator. Both listing were supplied to Quality Control to assure that all future failed parts were segregated for analysis.

Failed parts were then forwarded by Quality Control to the cognizant Reliability Engineering unit where failure symptoms were reviewed. The decision to perform failure analysis was dependent upon the current status of corrective action. If initiated, the parts were held for future dispositioning. If not initiated, the parts were sent either to the internal failure analysis laboratory, or to an outside laboratory such as the original manufacturer, RADC, or GE's Electronics Laboratory in Syracuse, New York. The laboratory selection was predicated on laboratory capabilities related to the suspected failure mechanism of parts to be evaluated.

These analyses normally resulted in a positive corrective action, principally because they were technically correct and conclusive. All laboratory reports were retained by Reliability Engineering for future reference. Documentation of a typical laboratory analysis report is shown in Figure 63.

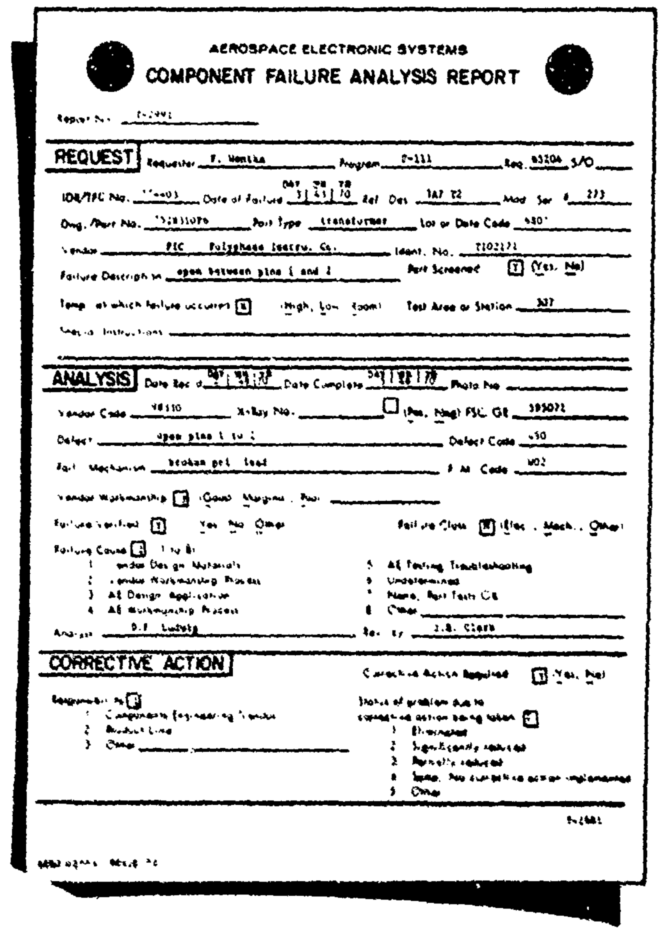
(2) Quality Assurance

(a) Quality Assurance Problem Book - The Quality Assurance Problem Book, initiated and controlled by the Quality Engineering organization, monitored design, workmanship, and material problems impacting production equipment. The Book utilized a Correction Plan format that identified responsibility, schedule milestones and provided visibility for cross-functional communication. Problems selected for documentation were those that could not be immediately resolved, had a series of discrete steps or events leading to a solution, and usually required cross-functional organization integration. A typical Problem Book entry is shown in Figure 64.

(b) Quality Reports - Quality Performance Reports, reflecting Inspection and Test Defects/Unit trends, were generated for subassembly, LRU and equipment levels and were based on three source documents: Test Failure Reports (TFR), Mechanical Inspection Reports (MIR), and Passed Test/Inspection Reports (PIR). Through a computerized data system, the basic data was structured to provide continuous visibility and control.

All reports were presented in a cumulative format to identify any gross shifts in quality performance. Major fluctuations were easily investigated by the use of subreports which identified the Quality performance at lower tier assemblies (i.e., LRU). Through weekly monitoring and subsequent cross-functional assignment of resolution responsibilities, problems were quickly addressed and subsequently corrected, controlled, or eliminated. Similarly, supplier material and/or major procurement items were identified and routinely corrected.

Test and Inspection Failure Reports - Specific Test and Inspection stations were designated at which Test Failure Reports and Mechanical Inspection Records were initiated by the Manufacturing Test/Inspection function for every equipment failure. In addition, MIRs were written for all material found discrepant during the manufacturing process, but prior to being submitted for inspection.



AEROSPACE ELECTRONIC SYSTEMS

COMPONENT FAILURE ANALYSIS REPORT

REQUEST Requester F. Wentka Program F-111 S/O

Date of Failure Ref Des Mod Ser

Part Type transformer Lot or Date Code

Vendor Ident. No.

Failure Description open between pins Part Screened (Yes, No)

Temp at which failure occurred (High, Low, Room) Test Area or Station

ANALYSIS Date Rec'd Date Complete Photo No

Vendor Code X-Ray No. (Pos, Neg) FSC GE

Defect open pins Defect Code

Fail. Mechanism broken pri. lead F.M. Code

Vendor Workmanship (Good, Marginal, Poor)

Failure Verified (Yes, No, Other) Failure Class (Elec., Mech., Other)

Failure Cause (1 to 8)

AE Testing Troubleshooting

Undetermined

Other

CORRECTIVE ACTION Corrective Action Required (Yes, No)

Product Line

Other

Other

Figure 63. Component Failure Analysis Report

The test (Figure 65) and inspection (Figure 66) reports served as a documented record of failure and defect occurrences for problem pattern identification and corrective action.

At acceptance test levels, failures were directly verified and screened by Quality Engineering personnel and the failure reports validated for accuracy prior to submission to data processing. This validation assured data integrity and provided immediate feedback of failure information, for on-the-spot investigation of individual problems.

F-111 QUALITY CONTROL PROBLEM SHEET

Sheet 1 Of 1

RTH CABINET	Problem No. 4	Date entered: 3/30/67	Entered by: F. Bodurtha	Follow Up Responsibility F. Bodurtha
7637307	Problem			References and Date
Filter	During F8111 mock-up, a mechanical interference sufficient to prevent assembly, was noted between the RTH cabinet and the All filter.			DCR 4-751 4/4/67
7618179 (4A11)				
	Est. Date Closed:	Date Closed: 6/13/67	Problem Entry Approved By:	

Date	Action	Responsibility
3/28/67	Three (3) other filters were found not to fit into one (1) other RTH Cabinet.	
	Dimensional check on filters (4) and cabinets (2) showed applicable dimensions within drawing tolerances.	
3/29/67	Engineering requested to re-dimension filter/cabinet concerning future assemblies and also rework of items on hand.	J. Breymaier
4/25/67	Tolerance study by Drafting shows that studs in cabinet panel should be moved .090" and filter slot should be opened. Target date for issuing CID is Wk 19.	J. Breymaier
6/13/67	Studs in bottom panel have been moved .070" away from front panel per CID 1T4N1988 effective S/N 136 on APQ-113 and CID 3T4N134 effective S/N 4 for APQ-114.	

Distribution:

J. Breymaier			
J. Fadrewski	C. Morgan	C. Toner	
R. Gardner	A. Schmitt	B. VanAtenam	
W. Higgins	R. Simpson		

Figure 64. Quality Control Problem Sheet

(e) Manufacturing Operator Report - Workmanship failures accounted for just over 50 percent of all failures detected at subassembly test level. Studies conducted during the various phases of the program revealed that 2 to 3 percent of the assembly operators were responsible for 45 to 50 percent of the total defects generated.

To identify and resolve workmanship problems, reports (Figure 67) were designed such that all operators within a functional work unit exceeding a specified threshold (average for their work unit) of defects were identified along with the type, classification, and number of defects generated. Attention was thereby focused on the small number of prime defect generators within a work unit. Manufacturing foremen were given "report cards" ranking them in order of performance of their work units. During the life of the program this identification, retraining, and/or reassigning of these prime defect contributors allowed for dramatic decreases in workmanship defects.

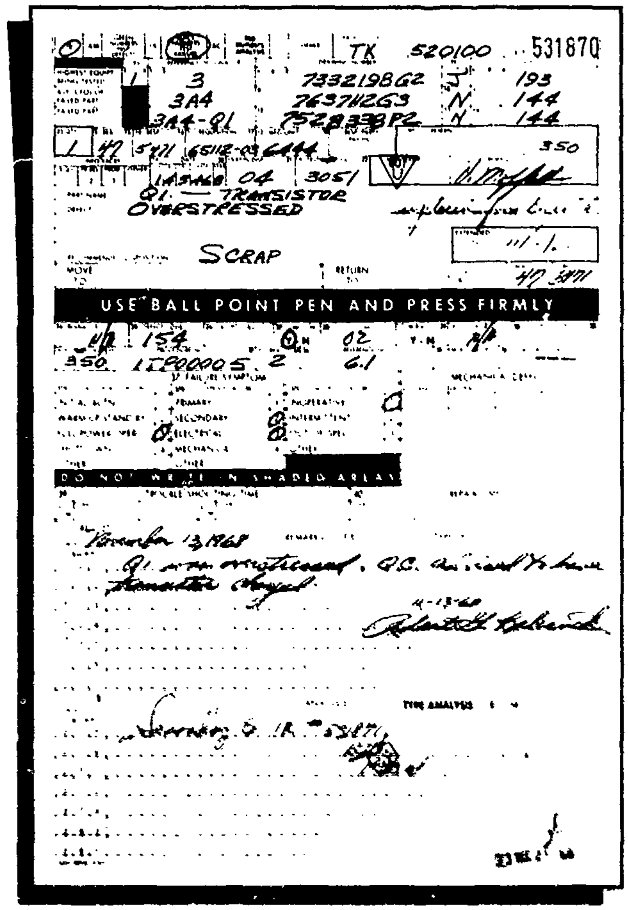
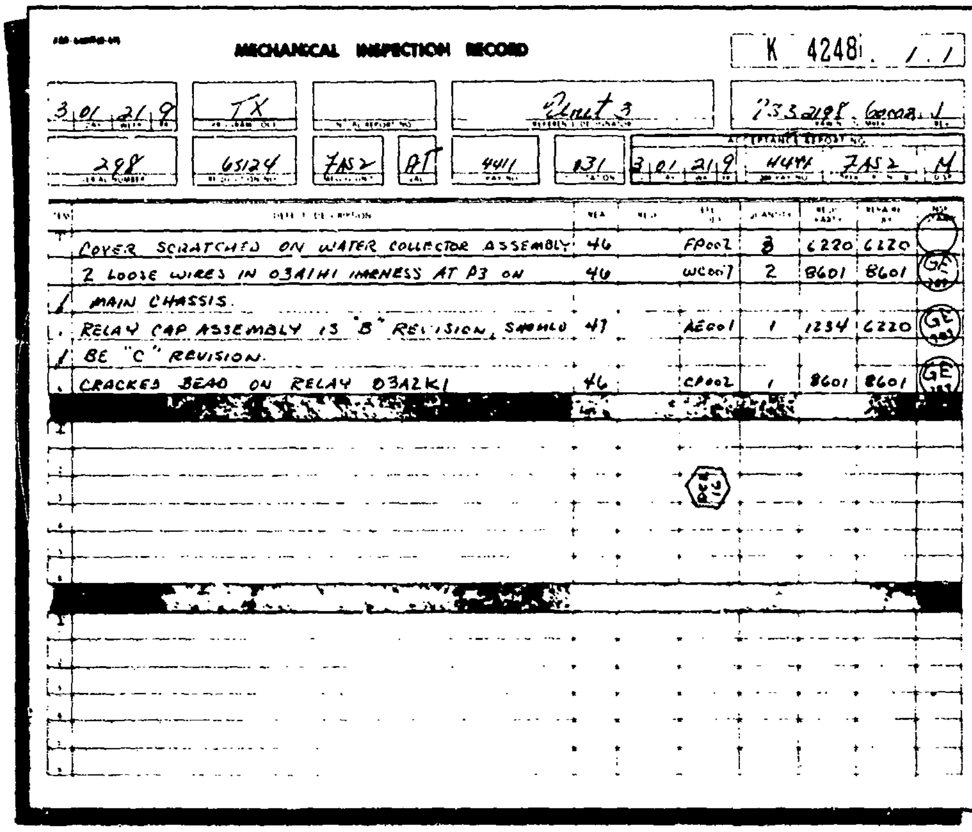

TK 520100 531870
3 7332198G2 193
3A4 7637142G3 N 144
3A4-Q1 7528338P2 N 144
Q1 — TRANSISTOR
OVERSTRESSED
SCRAP
USE BALL POINT PEN AND PRESS FIRMLY
DO NOT WRITE IN SHADED AREAS

Figure 65. Test Report

(3) Design Engineering - Engineering post-release design problems identification generally resulted from review of performance data taken during the Manufacturing tests. Just as Quality Problems were highlighted by means of a Quality Assurance Problem Book, design and performance problems were highlighted in what became informally known as the Engineering Problem Book.

Problem assignments within the book were normally relegated back to the cognizant design engineer. It was his responsibility to review the problem and draw up a preliminary action plan. The Plan usually consisted of individual action items designed to expose the source and define the steps required to eliminate the problem (see Figure 68). The individual(s) responsible for each action item were listed, as was the schedule for the completion of the task. Personnel external to the Engineering function were assigned with the concurrence of their immediate managers.



MECHANICAL INSPECTION RECORD

K 4248

COVER SCRATCHED ON WATER COLLECTOR ASSEMBLY	46	FP002	3	6220	6220
2 LOOSE WIRES IN 03A1H1 HARNESS AT P3 ON	46	WC007	2	8601	8601
MAIN CHASSIS.					
RELAY CAP ASSEMBLY IS "B" REVISION, SHOULD	47	AE001	1	1234	6220
BE "C" REVISION.					
CRACKED BEAD ON RELAY 03A2K1	46	CP002	1	8601	8601

Figure 66. Inspection Report

Each Correction Plan generated by the cognizant engineer was reviewed, approved, numbered, issued, and entered on the Problem Correction Plan Index (see Figure 68). At a minimum, each plan was formally reviewed and reissued bi-monthly.

When engineering changes in the form of ECP, CID or EN effort were required to close an action item, they were noted on the problem sheet and the index, and a final distribution was made.

Each corrective action plan was complete in that any peripheral information or resolutions that resulted (e.g., closer supplier surveillance, improved incoming test, modification of testing procedures, retrofit liability, and forward fit change liability), were also listed on the problem sheet.

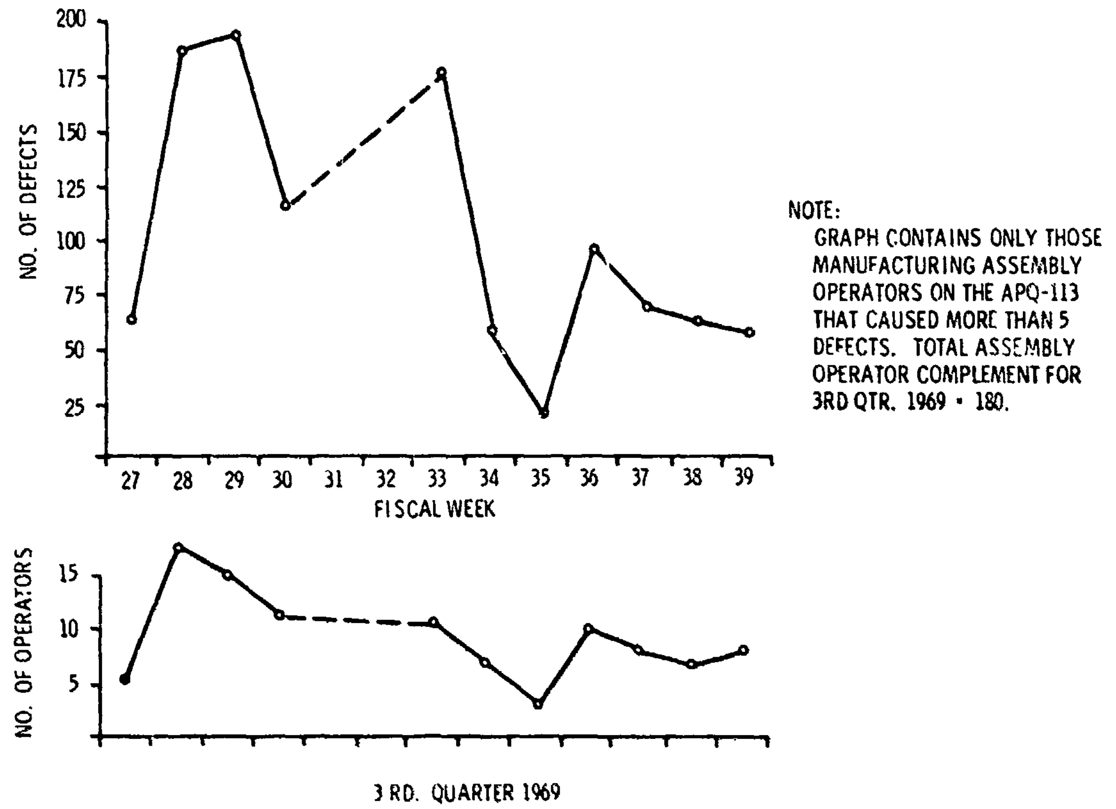


Figure 67. Manufacturing Operator Performance

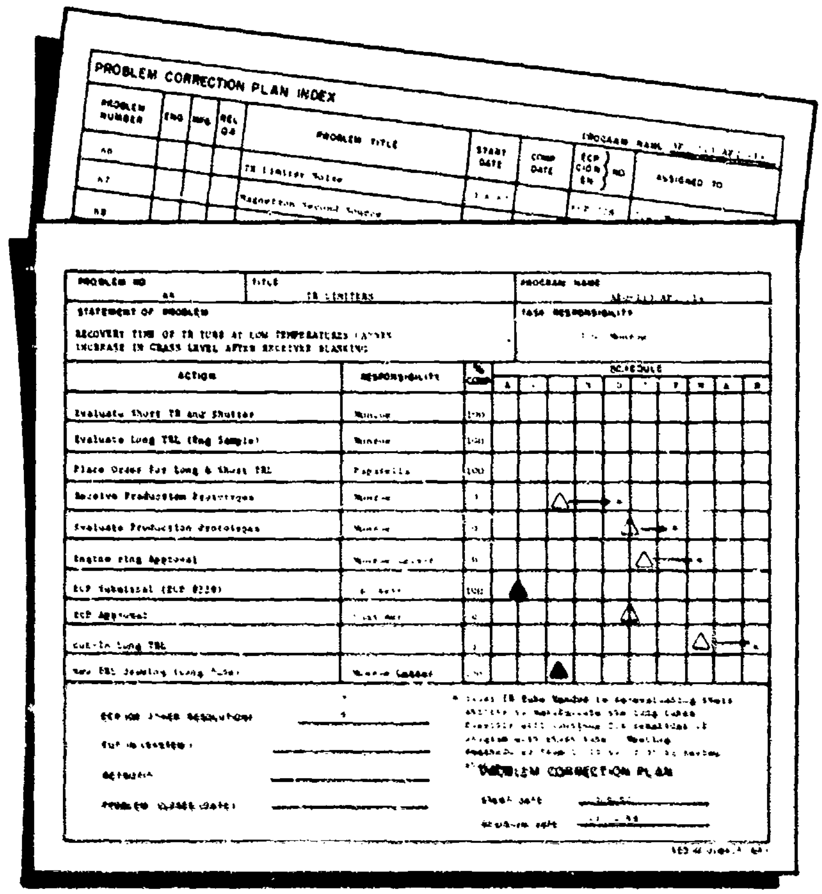


Figure 68. Problem Correction Plan

SECTION IV

PRODUCT ASSURANCE TEST PROGRAMS

A. INTRODUCTION

This section of the report addresses the equipment level Product Assurance Tests conducted on the radar programs studied, including Environmental Qualification, Reliability Evaluation, Reliability Qualification, and Reliability Acceptance Tests.

Each test is discussed, covering its objectives, structure, and time phasing. Test findings and results are compared and analyzed. Comparisons of the test results, particularly measured MTBFs, do not take into consideration differences in test stresses applied which are discussed in Section V.

Significant findings and conclusions are discussed and presented.

B. SUMMARY

The Product Assurance tests required and performed for the four radar programs are summarized in Table XVII. The table provides an overview of each test program, denotes the level of test (equipment vs LRU), number of equipments tested for each of the tests, and the equipment operating time when applicable.

The reliability tests delineated each have unique objectives but cannot be treated independently, if reliable equipment performance is to be achieved and sustained. The RET will allow for orderly reliability growth to a specified level of equipment performance (MTBF); the RQT will determine whether the contractor's equipment is compliant with the reliability requirement and prove that the RET program was effective. The RAT will ascertain if the reliability measured in RQT is being sustained throughout production equipment deliveries.

The following Product Assurance Tests are discussed in this section:

<u>EQT - Environmental Qualification Test</u>

Findings and conclusions based on the APQ-113/114/144 are discussed.

TABLE XVII. PRODUCT ASSURANCE TEST PROGRAMS SUMMARY

RADAR TYPE	EVALUATION TESTS			
	EQT	RET	RQT	RAT
120	PERFORMED AT THE EQUIP. LEVEL PER APPLICABLE TEST SPECIFICATION	NOT REQUIRED	5 SEPARATE TESTS: 9 RADARS FOR A TOTAL OF 188 HOURS	NOT PERFORMED
113	PERFORMED AT THE LRU LEVEL EXCEPT EQUIP. LEVEL EMI PER APPLICABLE TEST SPECIFICATION	13 RADARS FOR A TOTAL OF 10,000 HOURS*	1 TEST PERFORMED: 6 RADARS FOR A TOTAL OF 1413 HOURS	54 RADARS FOR A TOTAL OF 7071 HOURS
114	MRT, SYNCHRONIZER AND EQUIP. EMI TESTS ONLY	3 RADARS FOR A TOTAL OF 3838 HOURS	NOT REQUIRED	21 RADARS FOR A TOTAL OF 2750 HOURS
144	MRT AND EQUIP. EMI TESTS ONLY	3 RADARS FOR A TOTAL OF 990 HOURS	NOT REQUIRED	9 RADARS FOR A TOTAL OF 1178 HOURS

*LRU ENVIRONMENTAL AND RELIABILITY TEST

RET - Reliability Evaluation Test

Tests conducted on the APQ-113/114/144 are described, their purposes, findings, timeliness and achievements analyzed.

RQT - Reliability Qualification Test

The test results of the APQ-120 and APQ-113 RQT are discussed, analyzed, and comparisons drawn.

RAT - Reliability Acceptance Test

The needs, performance levels, timeliness, and results of the APQ-113/114/144 are discussed and analyzed. Comparisons to RQT results are also made.

C. CONCLUSIONS AND FINDINGS

- In the APQ-113 Environmental Qualification Test, 42% of the failures were design related, 20% parts, and 38% workmanship.
- 70% of the failures encountered in the APQ-113 EQT were in mechanical stress environments of vibration and shock

- Mechanical design and manufacturing planning received less attention in the APQ-113 RDT&E phase than electrical design.

- Timeliness of EQT and the RET program contributed significantly to APQ-113 RQT success.

- Initially demonstrated reliability - off-the-board - on the APQ-113 design was 10% of predicted.

- Failure distributions in the as-released off-the-board designs of the equipments studied during RET and EQT fit a 1/3-1/3-1/3 pattern - with design, parts and workmanship equally sharing the failure responsibility.

- Reliability Evaluation Tests are effective in detecting subtle time and exposure-dependent failures - that cannot be detected in a one "shot" test such as EQT.

- Design optimization alone yields a 30% compliant equipment - subtle parts and manufacturing caused failures will constrain the initial test measured reliability.

- The APQ-113 reliability requirements were 15 times as demanding as those on APQ-120 - assuming equal radar complexity.

- APQ-113 demonstrated a 35 times higher MTBF than APQ-120 (based on unnormalized test stress levels). APQ-113 achieved 112% of required; APQ-120, 50%.

- In the final RQT tests on APQ-113 and APQ-120, neither radar exhibited "equipment design" failures. APQ-120 reliability was constrained 33% by workmanship and 57% by parts, and the parts problems were attributed to workmanship causes.

- Higher parts reliability would have enhanced the performance in RQT of the equipments studied.

- During RQT testing, more failures were observed at cold temperatures than room or hot.

- The APQ-113/114/144 demonstrated reliability was continually monitored through a demanding and timely Reliability Acceptance Test program.

- RAT failure distribution on the APQ-113/114/144 programs consistently indicated that parts were ≈ 90% of the failures, indicating good control over requirements, and consistent with predictions.

D. RECOMMENDATIONS

- Reliability Qualification Test requirements should be strictly enforced and production release should be withheld until successful completion. Administratively/contractually, EQT and RQT should be combined, becoming a single production releasing element.

- Reliability Evaluation Tests need to be contractually specified, approved and scheduled, to provide assurance of timely reliability compliant equipment.

- Reliability Acceptance Test should be specified and implemented to maintain reliability levels during production cycles.

- Reliability Evaluation Tests should be of sufficient time duration and be at a minimum representative of field environments to afford detection of time/environment dependent failure mechanisms.

- Reliability Qualification Test acceptance plan criteria should be simplified to promote general understanding. The existing variety of confidence limits, measured values, specified values, demonstrated values, truncated tests cause unnecessary confusion.

E. TEST PROGRAM ANALYSIS

1. ENVIRONMENTAL QUALIFICATION TEST (EQT)

The Environmental Qualification Test (EQT), usually performed on one set of preproduction equipments, exposes equipment to its maximum design levels over a wide range of environmental conditions, with the ultimate aim of demonstrating the design's environmental integrity.

This test was performed on each of the four radars in compliance with contract requirements. On the APQ-114 and 144 programs, only significantly redesigned LRUs were included since the APQ-113 had been previously qualified. The unmodified LRUs were qualified by similarity. Timeliness of the EQT plays a significant role in achieving product design integrity. The APQ-120 radar EQT was initiated and completed in the production phase of the program, while the APQ-113 test was largely completed during the RDT&E phase, and in the case of the APQ-114 and 144 during the pre-release phases.

Tables XVIII and XIX reflect the type and quantity of failures encountered during the APQ-113 EQT. Seventy percent of all failures were encountered while the equipment was being subjected to mechanical environments (vibration and shock), indicating the relative lack of mechanical equipment maturity at the time of design release. Electrical design and circuit evaluations normally are given a higher priority than mechanical design effort. Development time assigned for the mechanical design is relatively

TABLE XVIII. ENVIRONMENTAL QUALIFICATION TEST FAILURE SUMMARY BY LRU, APQ-113

TEST ENVIRONMENTS	FAILURE DISTRIBUTION BY LRU						%
	A/P	ACU	RTM	SYNC	I/R	TOTAL	OF TOTAL
VIBRATION	5	26	50	15	30	126	68
SHOCK	1	0	1	0	3	5	3
TEMPERATURE ALTITUDE SHOCK STORAGE	5	5	13	7	6	37	19
HUMIDITY	0	4	7	4	3	18	10
SAND & DUST	0	0	0	0	0	0	0
TOTAL	12	35	71	26	42	186	100

TABLE XIX. ENVIRONMENTAL QUALIFICATION TEST FAILURE CATEGORIZATION, APQ-113

FAILURE CATEGORY	QUANTITY	PERCENT OF TOTAL
DESIGN	61	42
WORKMANSHIP	54	38
COMPONENT PARTS	29	20
TOTAL	144	100

short. The documented disciplines, practices and procedures usually provided for a typical avionics design are primarily applied to the electrical design.

Of the failures encountered in the APQ-113 (Table XIX), 42% were related to equipment design. Component parts accounted for 20% and workmanship failures accounted for the remaining 38%. This failure distribution emphasizes the necessity for timely EQT completion for corrective action addressing part and workmanship problems in addition to the design corrections identified. Figure 69 reflects the EQT's scheduling relative to the percentage of delivered production hardware.

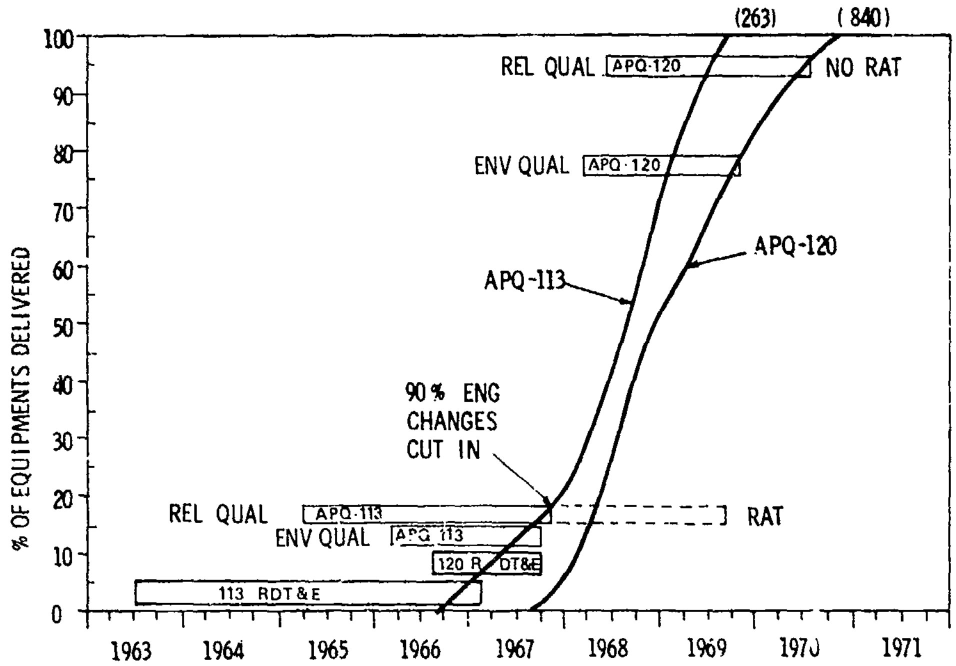


Figure 69. Evaluation Test Programs Timing

2. RELIABILITY EVALUATION TEST (RET)

Reliability Evaluation Tests are normally performed with pre-production equipment to the reliability qualification test environments for a specified test duration. The test provides for an orderly reliability growth through problem identification, resolution, and corrective action.

The initial APQ-113 reliability tests were identified as reliability pre-qualification tests, structured to identify design, component parts, and workmanship problems at an early stage, to effect timely corrective action and orderly reliability growth. Eight RDT&E equipments tested revealed that the initial measured MTBF was 10% of predicted and dramatically proved that a time-dependent test was necessary to achieve the reliability growth required to demonstrate the contract MTBF. A second reliability evaluation test program, with five equipments, was implemented to provide the additional reliability growth. Parallel to this, reliability growth was enhanced through LRU Environmental Screening Test Programs, which required the exposure of each LRU to the reliability qualification test temperature environment for a given number of cycles, with the constraint that the last two cycles be failure free. These combined test programs provided growth which resulted in the successful RQT demonstration.

As a result of the success obtained on the APQ-113, formal RET programs were planned and implemented for the APQ-114 and 144. Reliability requirements were achieved, on both programs, in a timely and cost effective manner.

The APQ-120 reliability program did not have the benefit of a Reliability Evaluation Test.

A comparative analysis of the failures encountered during the APQ-113 RET and the APQ-120 RQT No. 5 is portrayed in Table XX.

TABLE XX. APQ-113 RELIABILITY PRE-QUALIFICATION TEST VS APQ-120 RELIABILITY QUALIFICATION TEST

APQ-113		APQ-120
• PRE-QUAL TEST #1		• TEST #5
• 88 HR PREDICTION • 9.5 HR PERFORMANCE*	10%	• 45 HR PREDICTION (EST) • 4.3 HR PERFORMANCE*
• FAILURE DISTRIBUTION		• FAILURE DISTRIBUTION
• 32% WORKMANSHIP • 32% PARTS • 36% DESIGN	1/3	• 31% WORKMANSHIP • 37% PARTS • 32% DESIGN
• EQUIPMENT MATURITY		• EQUIPMENT MATURITY
• 7 PRODUCTION ITEMS		• 700 PRODUCTION ITEMS

* at 90% LCL

A significant observation is that approximately one-third of the total relevant failures encountered in RQT for both radars were related to design, one-third to workmanship and one-third to part failures. The results suggest that even with a perfectly designed equipment, the initial reliability performance will be constrained to one-third of its inherent capability. Further evidence of this distribution is indicated by examining Figure 70, where similar patterns were noted in the EQT tests - again - new products with limited or no maturity.

Analysis and investigation revealed that the RET failures in general, and the workmanship failures specifically, were more subtle part, design and manufacturing problems than typically uncovered during Environmental Qualification Test (EQT). Detection of these and effective corrective action demand meaningful test durations and multiple equipment samples on test. Equipment design-related failures can be attributed to "worst case" (circuit tolerance build-up) degradation and early wear-out conditions that generally are not detectable on every equipment produced and tested for only a relatively short duration. Reliability Evaluation Tests (long test durations, multiple equipments) are significantly effective in detecting and correcting subtle design defects.

3. RELIABILITY QUALIFICATION TEST (RQT)

Reliability Qualification Test is performed on a specified sample size of late preproduction equipments to demonstrate achievement of the contract MTBF requirement. The APQ-120 was subjected to five RQT tests, while two were performed on the APQ-113. For the first three tests, the APQ-120 failed the qualification prior to accumulating any relevant operating time. During the fourth and fifth tests, a total of 188 relevant hours were accumulated, at which point the testing was terminated.

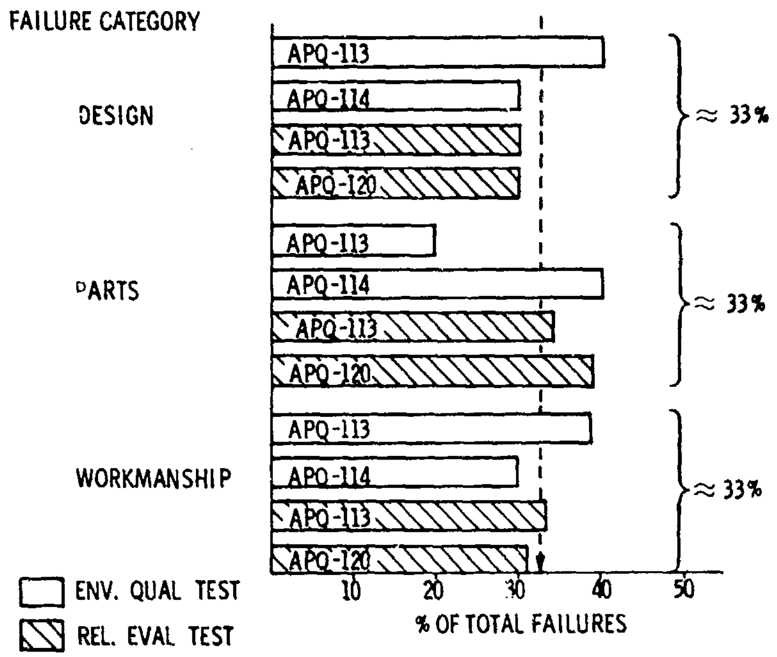


Figure 70. Comparative Failure Distributions-Environmental Qualification and Reliability Evaluation Tests

Since the RQT is the formal measurement of achieved equipment MTBF, the APQ-113 RQT No. 2 and the APQ-120 RQT No. 5 were compared as shown in Table XXI.

Although the functional equipment complexity for each of the radars was approximately the same, the APQ-113 contract MTBF requirement was 15 times greater than the APQ-120 (134 hours vs 9 hours at 90% LCL). The APQ-113 exceeded its contract requirement by 12% (152 hours vs 134 hours); the APQ-120 fell short of its requirement by 50% (4.3 hours vs 9 hours), a measurable reliability performance (MTBF) differential of 35 to 1. Differences in the environmental stress levels of the tests conducted account for some portion of the differences in results obtained (see Section V).

Other differences noted between the two RQTs are that the APQ-113 RQT included more equipments (6 vs 3) and significantly more test exposure hours per equipment (250 vs 30) which have the advantage of providing a greater opportunity for detection of subtle workmanship and "worst case" part drift related defects, which do not appear in each equipment produced or whose manifestation is environmentally and time dependent.

The failure distributions in both RQTs were grouped in three major failure categories - Design, Part, and Workmanship - the Part category being further divided into Design and Workmanship. One similarity readily apparent is that in both tests the total incidents experienced were reduced by approximately the same ratio (4:1) to arrive at the relevant failure classification.

TABLE XXI. RELIABILITY QUALIFICATION TEST COMPARISON

		APQ -113 *	APQ -120 **
REQUIREMENTS	CONTRACT M.T.B.F. @ 90% L.C.L (θ1)	134 HRS.	9 HRS
RESULTS	DEMONSTRATED MTBF @ 90% L.C.L.	152 HRS.	4.3 HRS.
TEST CONDITIONS	CHAMBER TEST LEVELS	-54°C TO 71°C ANT & ACU -54°C TO 132°C	-54° C TO 49° C
	VIBRATION	0.3g @ 25HZ	2.2g @ 57 HZ
	RELEVANT HOURS	1413	96
RESOURCES	NO. OF EQUIPMENTS	6	3
TEST DURATION	ELAPSED MONTHS	9	3
EFFICIENCY	AVG RELEVANT HRS ACCUMULATED/MONTH	157	32
INCIDENTS ***	PART DESIGN	14	0
	PART WORKMANSHIP	3	43
	DESIGN	0	0
	WORKMANSHIP	0	25
	UNDETERMINED OR NOT CONFIRMED	3	7
	TOTAL INCIDENTS	20	75
INCIDENT CATEGORIES BY % OF TOTAL INCIDENTS	PART INCIDENTS (%)	85	57
	DESIGN INCIDENTS (%)	0	0
	WORKMANSHIP INCIDENTS (%)	0	33
	UNDETERMINED OR NOT CONFIRMED (%)	15 (6)	10 (5)
INCIDENT CLASSIFICATION	RELEVANT FAILURES	5	16

* RQT II
** RQT #5
*** EXCLUDES TEST EQUIPMENT AND TEST OPERATOR INDUCED INCIDENTS

( ) - RET & RQT

In the Design (Equipment) category, neither radar experienced any failures. Both equipments apparently had achieved a high level of design maturity by the time these RQTs were conducted. For the APQ-113, this conclusion is supported by subsequent compliant Reliability Acceptance Test (RAT) data.

In the Workmanship category, the APQ-113 experienced no incidents. The reason for this absence can be attributed to LRU environmental screening test performed on a 100% basis to the RQT thermal environment with a strong corrective action program. The workmanship problems on the APQ-120 contributed to 33% and are attributable to the lack of an LRU environmental screening program. It was observed that 57% of the total incidents recorded on the APQ-120 were due to parts, but on the APQ-113, this category accounted for 85%.

Comparison of component part RQT incidents experienced points up another area where a significant difference existed. There were no component part "design" incidents for the APQ-120 RQT, while the APQ-113 reported 14 incidents. Of the APQ-113 incidents, 13 were associated with moving part items and were detected only after relatively long environmental exposure hours, which were not duplicated by any of the APQ-120 test samples.

As delineated in Table XXII, during RQT, more failures were observed during the cold temperature environment, when compared to other temperatures, by a factor of at least 2 to 1. When the failures are normalized to account for exposure time, the factor on the APQ-113 is 7 to 1. This further promulgates the necessity for performing 100% environmental screening test to insure the equipment is exposed to both temperature extremes. When the equipment is operated at ambient temperature, the parts may be subjected to a temperature rise due to the equipment's internal power dissipation; however, the parts will never be exposed to cold temperature. The RQT temperature cycle should simulate the worst case temperature and exposure periods the equipment will encounter in field use but in no event less than MIL-STD-781.

TABLE XXII. FAILURES OBSERVED AT COLD VS OTHER TEMPERATURES, APQ-120 VS APQ-113

	APQ-120 RQT								
	NO. OF FAILURES								
TEMPERATURE	RQT-1	RQT-2	RQT-3	RQT-4	RQT-5	TOTAL FAILURES	TOTAL * EXPOSURE HOURS	FAILURES PER 100 HRS.	RATIO FAIL/100 HRS at COLD vs OTHER TEMP
COLD	3	3	3	17	13	39	88	44	2.4
OTHER	-	-	-	17	3	20	100	20	

	APQ-113 RQT				
	NO. OF FAILURES				
TEMPERATURE	RQT	TOTAL FAILURES	TOTAL ** EXPOSURE HOURS	FAILURES PER 100 HRS.	RATIO FAIL/100 HRS at COLD vs OTHER TEMP
COLD	3	3	240	1.25	7.0
OTHER	2	2	1173	0.17	

APQ-120 RQT CYCLE = 9.6 HRS
APQ-113 RQT CYCLE = 24 HRS

* 47% OF THE APQ-120 RQT TEST CYCLE WAS BELOW ROOM AMBIENT (INCLUDES TRANSITION TO AND STABILIZATION AT -65° F)

** 17% OF THE APQ-113 RQT TEST CYCLE WAS BELOW ROOM AMBIENT (INCLUDES TRANSITION TO AND STABILIZATION AT -65° F)

4. RELIABILITY ACCEPTANCE TEST (RAT)

Reliability Acceptance Test is performed on a sampling basis (up to 100%) on production equipments to assure that compliant reliability is maintained throughout the production cycle. The test environment is similar or identical to the reliability qualification test environment and the sample size and test duration is dependent on the specific contract but based on MIL-STD-781. These tests were performed on the APQ-113/114/144 radars but were cancelled for the APQ-120. To ensure that the APQ-113/114/144 production equipments were compliant to the MTBF requirement of 134 hours, one out of every three production radars processed was subjected to RAT for a minimum of 130 hours each. During the five-year span, 84 representative samples of the production equipment were subjected to reliability acceptance tests. As indicated in Table XXIII, a total of 84 radars accumulated 10,999 relevant hours which resulted in an MTBF of 175 hours at 90% lower confidence level, objective evidence of the inherent reliability of the production equipments under the specified test conditions.

TABLE XXIII. RELIABILITY ACCEPTANCE TEST RESULTS

	APQ-113	APQ-114	APQ-144	TOTAL
No. OF EQUIPMENTS TESTED	54	21	9	84
RELEVANT HOURS ACCUMULATED	7071	2750	1178	10,999
MTBF AT 90% L.C.L.	161	145	147	176

The Reliability Acceptance Test provides both government and contractor management with a continuing quantitative assessment of the equipment being produced. It also helps to motivate the contractor to maintain the required reliability levels to avoid the penalties associated with failure.

A review of the APQ-113/114/144 failures experienced during RAT is summarized in Table XXIV.

The failure distribution by category remained approximately the same for each of the radar programs. Approximately 70% of the failures were parts, 17% were major procurement items, and about 13% were equipment workmanship defects. No equipment design defects were reported. The two areas in which the radar equipment manufacturer has greatest control, equipment design and equipment workmanship, account for a small percentage of the failures. This also emphasizes the benefits that could be obtained through upgraded parts quality.

TABLE XXIV. RELIABILITY ACCEPTANCE TEST FAILURE CATEGORIZATION

	APQ-113	APQ-114	APQ-144	TOTAL	% OF TOTAL
WORKMANSHIP	3	3	1	7	13
MAJOR PROCUREMENT	9	1	2	12	23
SPECIALTY ITEMS	6	3	1	10	19
SEMICONDUCTORS	14	4	0	18	35
PASSIVE DEVICES	3	2	0	5	10
TOTAL	35	13	4	52	100

The reliability program elements associated with controlling the failure rate of major procurement, specialty items, and component parts were highly effective in assuring that the reliability of these items were maintained throughout the production cycle. It is concluded that the level of part and LRU environmental screening employed on the APQ-113, -114 and -144 radar programs was a significant element for the sustained equipment reliability during the production delivery cycle.

One common ingredient greatly affecting all Reliability testing results is test timing. Ideally, EQT, RET, and RQT should be successively and successfully completed during the RDT&E phase. This will eliminate or substantially limit the accumulation of nonconforming production equipments, the need for costly retrofitting of production items, and excessive field maintenance costs.

SECTION V

ENVIRONMENTAL CONDITIONS

A. INTRODUCTION

This section of the study describes the specified environmental requirements and conditions prevailing during factory Qualification Tests (First Article and Reliability Qualification) and in-service use of the four radars (APQ-113, -114, -120, -144). The data for this section was obtained and collected from various USAF sources, the two aircraft contractors, and the radar manufacturers.

This information is presented to facilitate a retrospective analysis of the environmental conditions prevailing during the factory Qualification Tests for each radar. Comparisons are made between the severity level and duration of environmental stresses encountered in RQT versus field deployment. Other environmental conditions, presently absent in MIL-STD-781 specified tests, but prevalent in field operation, are discussed.

This section is divided into several subsections treating the various aspects of the environmental requirements and conditions. Each subsection is prefaced by its objective and conclusion, and is concluded by a detailed analysis.

B. SUMMARY

The following environmental analysis and aspects pertaining to the radar reliability performance in the factory and field are contained in this section:

> Environmental Requirements - Summaries and comparisons are made of the environmental requirements and conditions for the radar design, design qualification tests, reliability qualification tests and field environment.
>
> Reliability Qualification Specification - MIL-STD-781A and MIL-R-26667A conditions and requirements are described and defined to provide a basis for comparative analysis to the tests as performed.
>
> Reliability Qualification Test Conditions - The tests as performed are described and the differences from specifications identified.
>
> Reliability Qualification Test Comparisons - The environmental test conditions applied to the APQ-120 and APQ-113 114 144 during RQT are compared and differences analyzed.

Field vs RQT Environmental Exposure - The differences in thermal, vibration and humidity conditions are explored and analyzed.

C. FINDINGS AND CONCLUSIONS

1. Vibration

Flight vibration measured on the F-111 and the F-4E aircraft is random in character and extends beyond 2000 Hz. Qualification testing was generally limited to sine excitation to 500 Hz with resonant dwells. Vibration during Reliability Demonstration Testing is at a fixed low frequency. Vibration levels of F-4E in flight are more severe than those of F-111; APQ-120, however, by virtue of being vibration isolated, sees vibration levels comparable to APQ-113/114/144.

2. Temperature

- APQ-113/114/144 Radars

  The APQ-113/114/144 radars are supplied with cooling air during flight at very low temperatures, which are also significantly lower than those supplied during Reliability Qualification. Also for a short period in flight, cooling air is supplied at temperatures significantly higher than during RQT. These facts caused the field environmental profile to be more severe than the Reliability Qualification environment.

- APQ-120 Radar

  The cooling air supplied to the APQ-120 radar during flight are at temperatures that are more benign to the equipment, because they remain substantially above the low temperatures and are at greater flow rates than that supplied during Reliability Qualification Test. This caused the RQT environmental profile to be significantly more severe than the flight environmental profile.

3. RQT Deviation From MIL-Reliability Test Specifications

- APQ-120 Radar

  The APQ-120 radar was subjected to an unusual test condition, the quantitative effect of which is not known, during the cold part of the temperature cycle. The flow of cooling air through the forward radar assembly was reversed, resulting in a large percentage of the forced air-cooled components being subjected to a higher thermal shock than required by MIL-STD-781A.

- APQ-113/114/144 Radars

  The specifications for APQ-113/114/144 radar's RQT prescribed maximum ambient temperatures greatly in excess of the require-

ments of MIL-R-26667 (160°F for the electronics bay LRUs and 270°F for the radome installed equipment versus 131°F required by MIL-R-26667). This is a very significant deviation from the military specification, especially for equipment cooled by free convection.

4. RQT Long Term Environmental Exposure

The long term effects of exposure to environmental conditions other than temperature extremes and thermal cycling are not adequately simulated by the Reliability Demonstration tests presently specified. Specifically, this applies to the detrimental effect of prolonged exposure to humidity (with contaminants present in the field) and the effect of extended exposure to random vibration.

First Article Qualification Testing does allow evaluation of the short-term effects of exposure to relatively high environmental levels; however, field performance problems indicate inadequacies in at least some of these environmental tests.

5. RQT Operation In Environment

The operational requirements of both Reliability Qualification Tests were defined so that operation of the equipments was not required during the cold portion of the test, even though power was applied at the start of the cold to heat transition. For the APQ-113/114/144, this constituted a milder exposure than experienced in flight, while for the APQ-120 it represented a more severe requirement. It further was evident that electrical tests during temperature transitions - both cooling and heating - is not required, again not duplicating actual field operational environments.

6. Humidity

No quantitative data was available for field encountered conditions. The humidity conditions during RQT were not controlled and were mild in comparison to the actual field use. Both radars passed the First Article Qualification Test for humidity.

D. RECOMMENDATIONS

- Simulate flight encountered vibration environment in EQT by changing the fixed frequency sinusoidal condition to a random type. In addition, a study should be conducted to determine, based on hard failure data, if a similar change to RQT specifications is warranted and cost effective.

- Adjust the profile (e.g., exposure duration, temperature limits) of the environmental cycle in RQT and RAT to be consistent with and as severe as flight conditions, but never below MIL-STD-781 requirements.

- Add a requirement to MIL-STD-781B (Reliability Qualification & Acceptance Tests) to operate the equipment and perform measurements in low temperature and during temperature transitioning.

E. ANALYSIS

1. ENVIRONMENTAL CONDITIONS SUMMARY

A summary of the environmental conditions for the APQ-113, -114, and -144 and the APQ-120 radar is presented in Table XXV. This summary relates the design requirements, field conditions, Reliability Qualification Test Specifications, and the applicable Reliability Test Standards.

Columns A and E list the specified environmental condition limits for each radar. Columns B and F contain a condensation of field/flight environmental exposure information obtained from several sources but primarily from flight test data. When flight data were not available, the information presented is based on a mixture of General Dynamics and McDonnell Douglas experience, and limited test data combined with analysis.

The remaining four columns describe the Reliability Qualification Test actually performed (columns C and G for the APQ-113, -114 and -144, and the APQ-120 respectively) and the tests required by the Reliability Test Specifications on which these tests were based (column D: MIL-R-26667A for the APQ-113, -114 and -144, column H: MIL-STD-781A for the APQ-120).

Table XXV (and the subsequent discussion) is limited only to these environments to which the equipment was subjected during Reliability Qualification Testing. First Article Qualification Testing programs were conducted* on both radars including, in addition to thermal exposure and vibration, such standard MIL-Spec tests as shock, humidity, altitude, sand and dust, which are known to be primary or secondary causes of failure, either individually or in combinations.

A logical extension to the work contained herein would be an in-depth investigation of the adequacy of present design criteria and controlled environmental testing programs as related to measured field environments.

A comparison of field to RQT environmental conditions and the differences between the specified RQT conditions and the applicable MIL-Spec are discussed in subsequent subsections.

2. RELIABILITY QUALIFICATION TEST ENVIRONMENTS

a. Objective

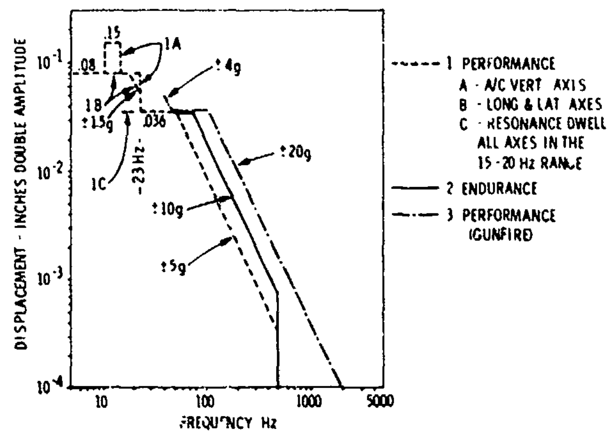
The objective of this subsection is to compare the RQT environmental profile for each of the two radars with the applicable MIL-Specification for Reliability Tests called out in the contractual documentation. Severity of tests in terms of environmental stresses, duration of exposures to environmental extremes will be compared and departures from the referenced MIL-Specifications identified.

*First Article Qualification Test report for the APQ-120 was not part of the data package studied or obtained.

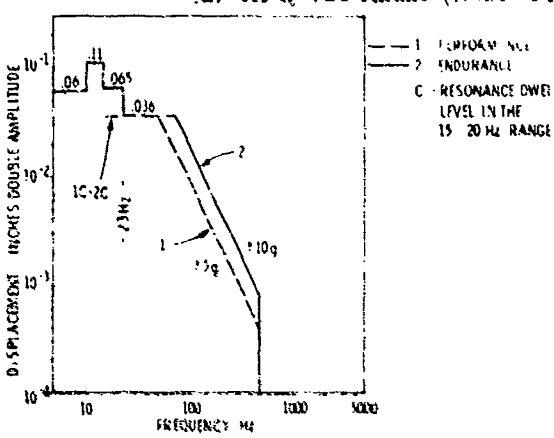
TABLE XXV. ENVIRONMENTAL COMPARISONS

[illegible]	[illegible]				APG 120			
	A	B	C	D	E	F	G	H
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	DESIGN REQ'T	* FIELD (AIRCRAFT) CONDITIONS (F-4E)	REL DEMO TEST	MIL STD 781A TEST LEVEL E
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	160°F (71°C) STEADY STATE 203°F (95°C) FOR 30 MIN FOR NOSE EQUIPMENT 120°F (49°C) S.S. 160°F (71°C) FOR 30 MIN FOR CABIN EQUIPMENT	160°F (76°C) SEA LEVEL, MAX POWER, HOT DAY 78°F (26°C) 35,000 FT CRUISE, HOT DAY FOR NOSE COMPARTMENT	120°F (49°C)	131°F (55°C)
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-65°F (-54°C)	56°F (13°C) FOR ALL FLIGHT CONDITIONS. LOGICALLY NOT BELOW -65°F FOR TRANSIENT GROUND OPERATION	-65°F (-54°C)	-65°F (-54°C)
[illegible]	[illegible]	[illegible]	[illegible]	MAXIMUM DESIGN TEMPERATURE	+160°F (+71°C)	91°F (32°C) IN FLIGHT FOR NOSE COMPARTMENT	85°F (29°C)	MAXIMUM DESIGN TEMPERATURE
[illegible]	[illegible]	[illegible]	[illegible]	MINIMUM DESIGN TEMPERATURE	+23°F (-5°C)	40°F (5°C) IN FLIGHT	-65°F (-54°C) NON-OPERATING	MINIMUM DESIGN TEMPERATURE
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible] FOR NOSE EQUIPMENT OTHER EQUIPMENT NATURAL CONVECTION COOLED	5.42 LB/MIN/KW (27.4 LB/MIN TOTAL FLOW) AT 98°F (37°C)	APPROX 2.58	MINIMUM DESIGN FLOW
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible] FOR NOSE EQUIPMENT OTHER EQUIPMENT NATURAL CONVECTION COOLED	5.78 LB/MIN/KW (29.64 LB/MIN TOTAL FLOW) MAXIMUM AT [illegible] 2.41 LB/MIN/KW (12.4 LB/MIN TOTAL FLOW) MINIMUM AT 40°F (5°C)	UNKNOWN. COOLING AIR REVERSE FLOWED THROUGH THE EQUIPMENT AT COLD. SEE TEXT FOR MORE DETAIL	MAXIMUM DESIGN FLOW
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	FIGURE 21	2.5G RMS RANDOM AT MACH 1.8 AND 30,000 FT ALTITUDE. REF TO TEXT FOR MORE DETAIL	.017 D.A. (2.2G) AT 57 Hz 10 MIN/HOUR OF "ON" TIME	2.2G AT ANY NON-RESONANT FREQUENCY BETWEEN 20 & 60 Hz
[illegible]	[illegible]	—	[illegible]	[illegible]	[illegible] 120V		UNKNOWN ASSUMED NOMINAL $^{+5}_{-2}$%	NOMINAL $^{+5}_{-2}$%
[illegible]	N.A	N.A	[illegible]	ON DURING HOT PART OF CYCLE, OFF DURING COLD PART OF CYCLE [illegible]	N.A	N.A	ON DURING HOT PART OF CYCLE, OFF DURING COLD PART OF CYCLE (62.5%)	ON DURING HOT PART OF CYCLE, OFF DURING COLD PART OF CYCLE (61.2%)

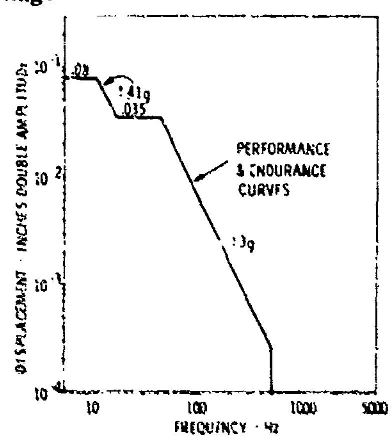
* [illegible]



(a) APQ-120 Radar (Nose) Package



(b) APQ-120 Forward Cockpit



(c) Aft Cockpit - 51 Range Indicator

Figure 71. Vibration Qualification Test Levels

b. Summary

- The upper temperature limit of the test chamber for APQ-120 RQT (+120°F) was below the MIL-STD-781A specified +131°F. The rate of chamber ambient temperature change was 3.2°F/minute, below the MIL-STD-781A specified minimum of 9°F/minute. Other environmental conditions were conformant with the MIL-STD-781A requirement.

- APQ-120 was subjected to a very severe thermal shock (25°F/minute) due to the cooling air supply method when transitioning from cold to hot.

- The upper temperature limits of test chamber for APQ-113/114/144 RQT (+270°F for Antenna Assembly, +160°F for other LRUs) were above the MIL-R-26667A specified +131°F.

- APQ-120 was subjected to approximately seven times higher vibration level than APQ-113/114/144 (2.2G versus 0.32G); however, the total vibration exposure time in a 24-hour test period was 60% longer for the APQ-113/114/144 as compared to APQ-120 (240 minutes versus 151 minutes).

c. Military Specification Description

(1) MIL-STD-781A

Contractual documentation for the APQ-120 (McDonnell Douglas document SCD 53-870050) specifies that Reliability Qualification Test be conducted in accordance with the requirements of MIL-STD-781A, Test Level E (modified). The test conditions of Test Level E (unmodified) call for thermal cycling operation of equipments subjected to test, with concurrent periodic vibration at a fixed nonresonant frequency. The ambient temperature extremes are -65°F (-54°C) and +131°F (+55°C) as shown in Figure 72. The rate of temperature change of the thermal medium when transitioning from hot to cold and vice versa shall average not less than 5°C/minute. Operation of the equipment under test is required from the time the environmental chamber temperature control is set for the high temperature limit. During the period of radar operation, fixed frequency vibration at 2.2G ±10% is imposed for a period of at least ten minutes out of each hour of equipment ON-time, at a nonresonant frequency between 20 and 60 Hz. The vibration frequency is selected during a vibration survey which precedes the formal testing. If the equipment under test is designed to meet a less severe vibration requirement than 2.2G at the frequency selected for the test, then this specification allows reduction of the vibration level to that specified as the design requirement. In general the direction of vibration is not specified unless the configuration is such that one direction is obviously more critical.

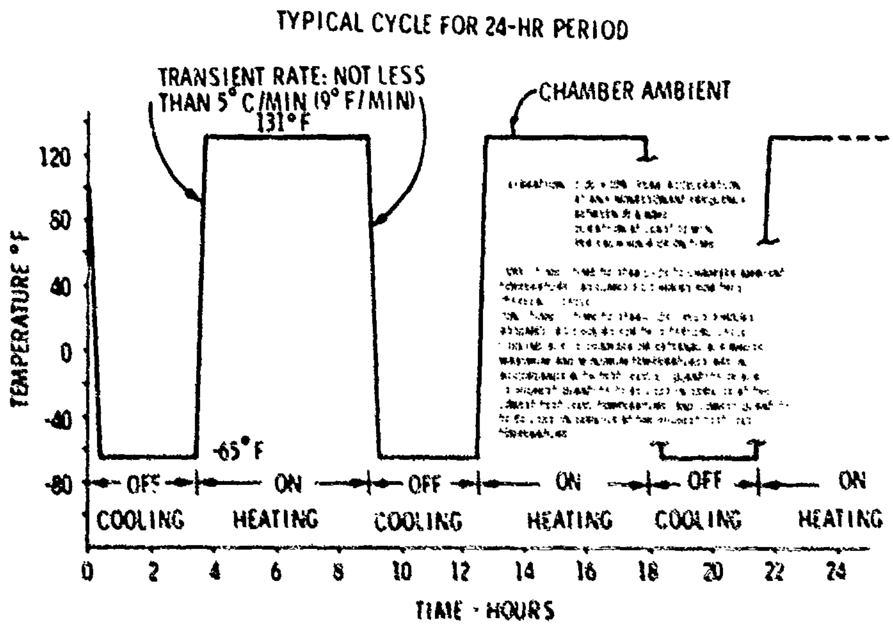


Figure 72. Environmental Test Cycle, MIL-STD-781A Test Level E

The thermal cycle times are established by conducting a thermal survey during which the component of greatest thermal inertia is identified along with the time required for its stabilization. Stabilization is measured under two conditions: (1) after

the temperature transition from high to low while equipment is turned off and (2) after the temperature transition from low to high with equipment operating. The specification requires the duration of the cold part of the cycle to be the time required to stabilize at cold. Three and one half hours were used in portraying a typical cycle shown in Figure 72. The duration of the high temperature part of the cycle is specified to be the time required to stabilize at the high temperature, plus two additional hours. A 3-1/2 hour stabilization time is used, yielding a total duration for this part of the cycle of 5-1/2 hours; the total time for each cycle is therefore 9 hours.

Cooling air is to be supplied throughout the cycle, either directly from the chamber or from an external conditioning source. In general, the most economical source is directly from the chamber and this would be the source used unless the required cooling air temperatures are different from the chamber ambient. The temperatures and flow rates to be supplied are defined in the specification to be the maximum temperature and the minimum rate of flow (per the equipment specification) when the chamber temperature is at the highest level, and at the minimum temperature and maximum rate of flow when the chamber temperature is at its lowest level. Cooling air temperature for forced-air cooled equipment would roughly follow the transition cycle from hot to cold, or cold to hot, changing at not less than 5°C/minute (9°F per minute), and leveling out at the equipment specification maximum and minimum values.

During a 24-hour period, the equipment operates for 14.7 hours, and is subjected to vibration for a total time period of 147 minutes.

(2) MIL-R-26667A

The contractual documentation for the APQ-113 radar (General Dynamics Specification FZM 12073) specifies that the Reliability Qualification Test be conducted in accordance with requirements of MIL-R-26667A, Test Level 3 (modified). Test Level 3 (unmodified) combines ambient temperature and cooling air temperature cycling with low level, fixed frequency vibration and varying modes of operation of the equipment under test. The ambient temperature is cycled between the same limits as defined for MIL-STD-781A, test level E, namely -65°F (-54°C) and +131°F (+55°C). The rate of temperature change of the thermal medium during transition time from one extreme to the other shall not be less than 5°C/minute. The cycle defined is based on stabilization time data obtained during the same type of thermal survey as previously described. The requirements of this specification differ from those of MIL-STD-781A in that the hot portion of the cycle is specified to be three hours, plus sufficient time to stabilize versus time to stabilize plus two hours for the MIL-STD-781A. Thus the operation of equipment for 4-1/2 hours, as shown in Figure 73, provides sufficient time at high temperature to allow a complete electrical performance test. The duration of the cold part of the cycle is the 3-1/2 hours required for thermal stabilization. The total time required for a complete cycle is therefore 8 hours, allowing 3 complete cycles in a 24-hour period.

Cooling air is supplied continuously at the maximum air temperature and the lowest flow rate for the hot part of the cycle, and the minimum air temperature at the highest flow rate for the cold part of the cycle. Cooling air temperature transition would follow the chamber transitions closely, and level off at the maximum and minimum temperature levels defined by the equipment specification.

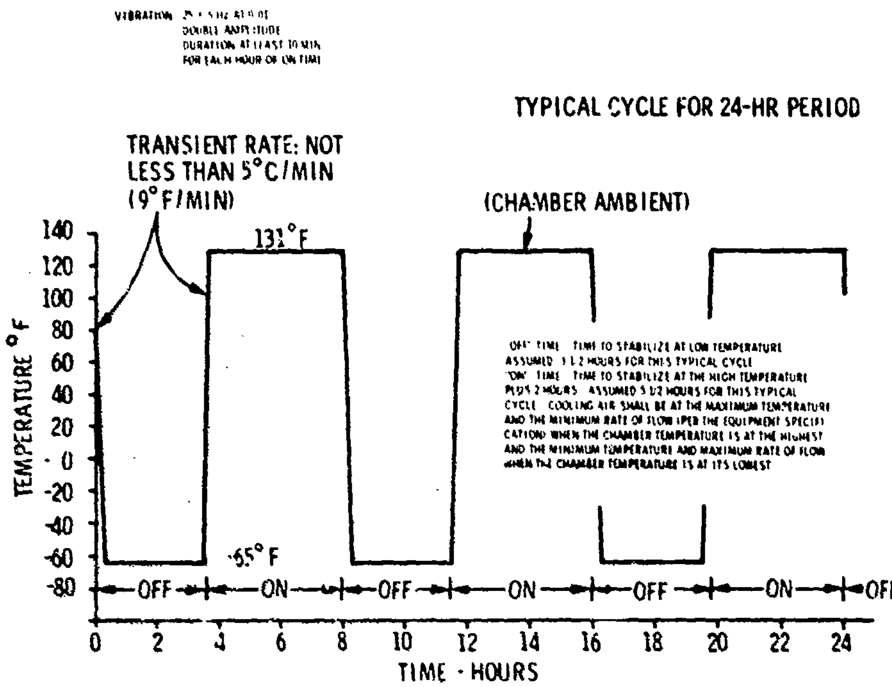


Figure 73. Environmental Test Cycle, MIL-R-26667A, Test Level 3

d. RQT Description Departures

(1) Departures from MIL Reliability Test Specifications

The actual environmental conditions during Reliability Qualification Tests deviated in accordance with contractual specification from the referenced MIL reliability test specifications. The departures from the specified limits are enumerated in the following discussion.

(a) APQ-120 RQT - The test cycle used during RQT of APQ-120, as portrayed in Figure 74, deviated from MIL-STD-781A, Test Level E in two respects. First, the maximum chamber ambient temperature limit was 120°F (49°C) versus Test Level E specified 131°F (55°C); second, the rate of change of chamber ambient temperature was 3.2°F/minute (1.8°C/minute). It is to be noted that the upper temperature design limit for the cockpit was 120°F (49°C).

(b) APQ-113/114/144 RQT - The test cycle used during RQT of APQ-113/114/144 is depicted in Figure 75. As evident from the figure, the maximum range of chamber ambient temperature is from -65°F (-54°C) to +160°F (+71°C) for all LRUs except the Antenna Assembly, which, because of its location in the radome of the F-111, was tested over a temperature range from -65°F (-54°C) to +270°F (+132°C). Figure 76 shows the APQ-113 reliability test area facilities with the dual chamber set up to

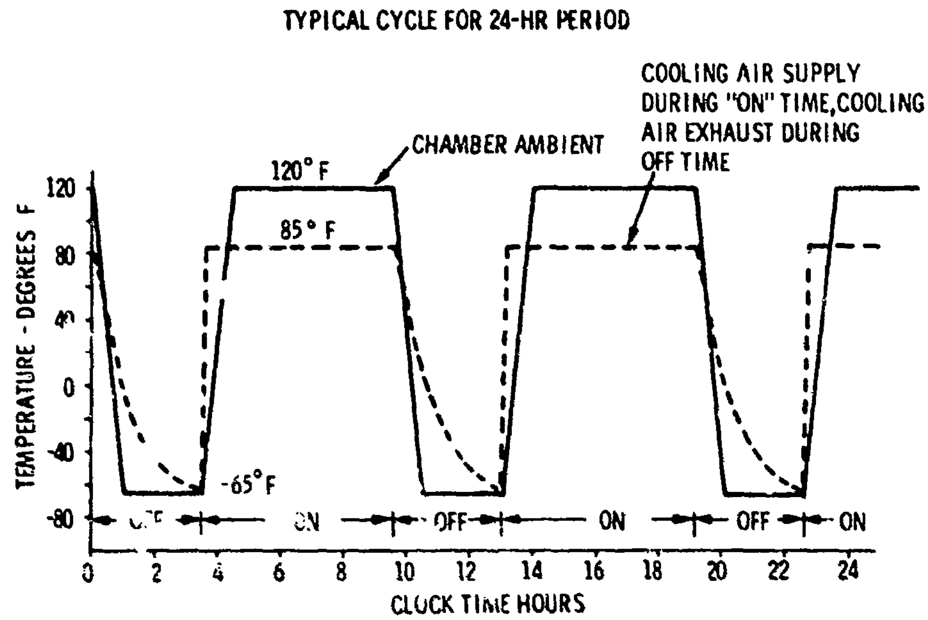


Figure 74. Reliability Qualification Test Cycle, APQ-120

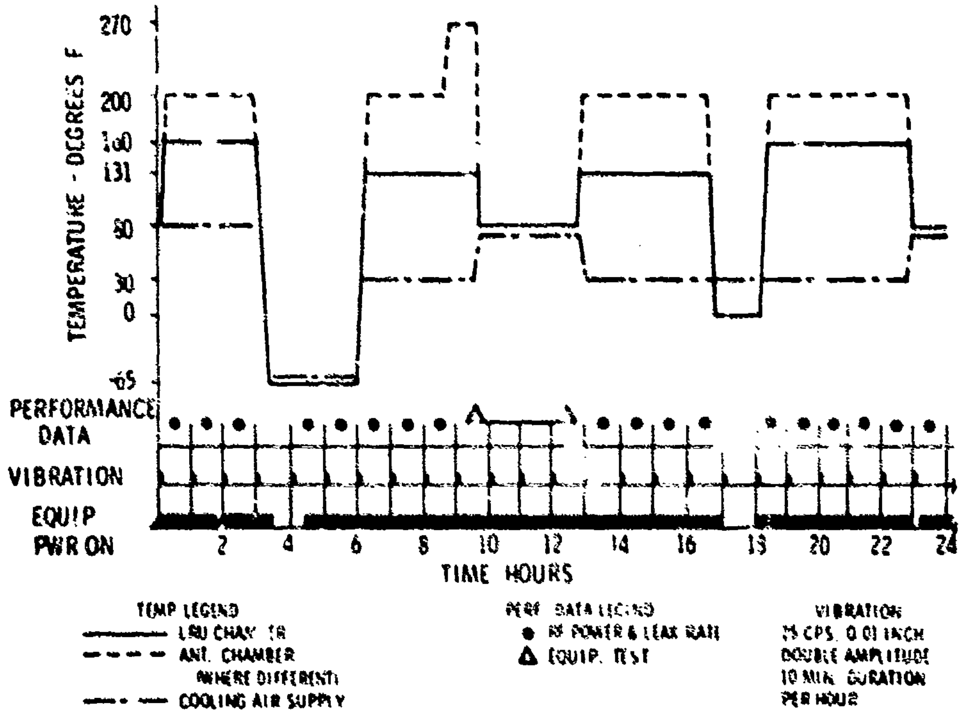


Figure 75. Reliability Qualification Test Cycle, APQ-113/114/144

Figure 76. Reliability Test Area, APQ-113

simulate the equipment bay and the radome environments. In the foreground, the left-hand chamber contains the RTM, Synchronizer, and Indicator LRUs, while the right-hand chamber holds the Antenna, Pedestal, and Antenna Control Unit. Both of the upper temperature ranges are in excess of the MIL-R-26667A, Test Level 3 limits of +131°F (+55°C). Another departure from that specification (i.e., more severe) was the total vibration time in a 24-hour period.

The equipment under test is subjected to vibration for a period of at least 10 minutes out of each hour of system operation. Vibration is specified as 25 Hz ±5 Hz at an applied double amplitude of 0.010 inch. This is equivalent to a normal level of ±0.32 G. Equipment normally isolated (as is the APQ-120) is tested hard-mounted to the vibration machine. The direction of vibration is not critical.

For the cycle developed here and shown in Figure 73, the equipment is operated for a period of 13.5 hours, and is vibrated for a total of 135 minutes during a 24-hour test period.

The level and the frequency were as defined by MIL-R-26667A; however, the duration of vibration exceeds by 105 minutes the requirement of this specification for each 24 hours of testing. Note that the equipment design specification calls out 0.01 inch double

amplitude at 25 Hz, and that the Design Qualification Test input at 25 Hz was at this level; therefore, it can be concluded that the RQT levels were compatible to the design requirements.

APQ-113/114/144 had performance measurements made every hour of operation, regardless of cycle, and a full test performed once each 24-hour period at room ambient, which was more than required by MIL-R-26667A (i.e., each performance parameter tested once per day). At this point it is worthwhile to contrast the measurement philosophy of APQ-120 in RQT (fully compliant with MIL-STD-781A) with that of APQ-113/114/144. In the case of APQ-120, electrical performance was monitored only during transition from cold to hot and during operation following stabilization at hot; however, the analysis of failure data from the RQT revealed that majority of failures were observed during the cold portion of the thermal cycle.

(2) Cooling Air

Cooling air merits a separate discussion. In the case of APQ-120 it provided a very severe thermal shock during transition from low to high temperature and might have been the cause of some RQT failures.

For the APQ-120, as shown in Figure 74, the cooling air was supplied to the equipment under test during the high temperature part of the cycle (equipment operating) at the specified flow rate and at a maximum temperature of 85°F (29°C) from an external source. During the cold part of the cycle (equipment nonoperating), the cooling air flow was reversed, i.e., the cooling air entered the equipment through the exhaust openings and was exhausted through the normal inlet. This procedure accounts for the rapid change from low to high temperatures of 25°F/minute (13.8°C/minute) and the very slow change (as measured by the inlet thermocouple) from high to low of 2.5°F/minute (1.39°C/minute).

APQ-113/114/144 had the cooling air temperature cycled, as shown in Figure 75, between -65°F (-54°C) and -80°F (-27°C). The maximum cooling air temperature of [illegible]°F (49°C) was defined by the equipment specification as the maximum cooling air [illegible] temperature for ground operation, with flow rate increased for this condition over that supplied at 80°F.

The cooling air flow rates are different for each LRU since they are based on total heat load. The total heat load is defined as the maximum electrical dissipation plus heat added to the LRU while operating in its highest temperature ambient. The exhaust air temperature and the average cooling air temperature, are therefore related to actual mode of operation, and ambient temperature for each step during the test cycle. This leads to fairly large variations in temperature and temperature shock among the LRUs, for different steps during the test cycle. This effect is illustrated in Figure 77 for the Receiver-Transmitter-Modulator (RTM) LRU and Figure 78 for the Antenna Control Unit (ACU) LRU, the two units which are exposed to the widest swings of external ambient temperature and also representing the two extremes in power dissipation, among all the LRUs. The RTM dissipates a large quantity of heat, is thermally designed for ambient temperature of 160°F (71°C) and is therefore relatively unaffected by the external ambient when compared with the low power dissipation ACU, designed for an ambient of 270°F (132°C) maximum.

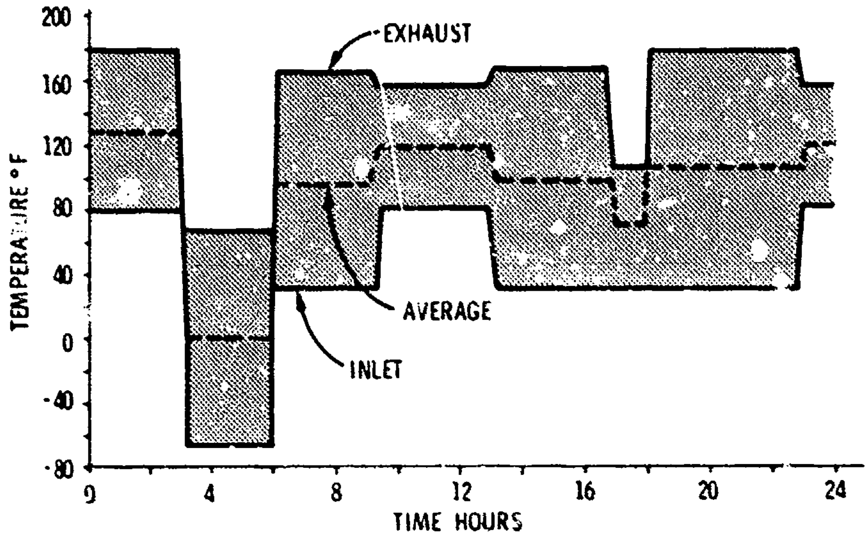


Figure 77. Reliability Qualification Test Cooling Air Temperatures, APQ-113 Receiver-Transmitter-Modulator

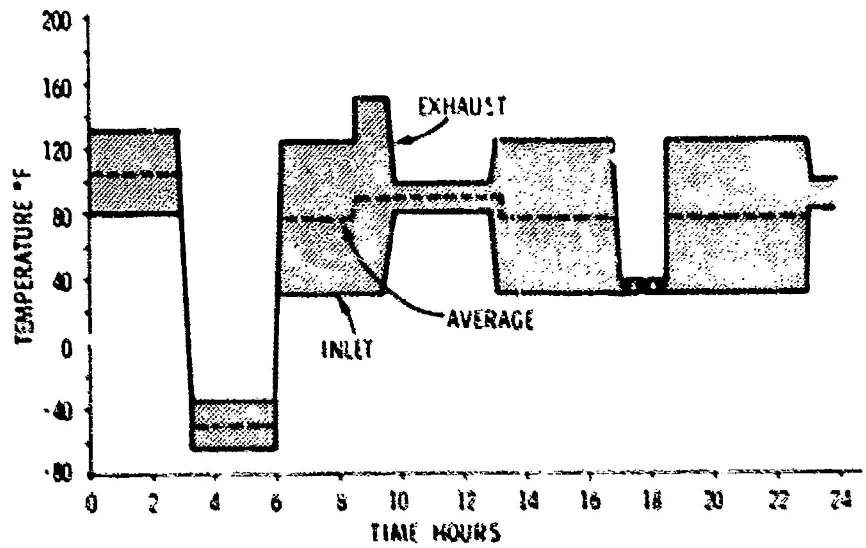


Figure 78. Reliability Qualification Test Cooling Air Temperatures, APQ-113 Antenna Control Unit

c. Comparison of RQT's Severity - APQ-120 vs APQ-113/114/144

Table XXVI presents in a matrix format salient features of the RQT for each radar to allow a comparison of the relative severity of test conditions. For each test attribute listed, there is a corresponding condition for the applicable MIL-Spec.

TABLE XXVI. ENVIRONMENTAL STRESS LEVEL COMPARISON, RELIABILITY QUALIFICATION TEST, 24-HOUR TIME PERIOD

	AN/APQ-113	MIL-R-26667 TEST LEVEL 3	AN/APQ-120	MIL-STD-781A TEST LEVEL E
NUMBER OF TIMES EQUIPMENT UNDER TEST TURNED ON, OR OFF	6	6	5	5.3
TOTAL CHANGE IN COOLING AIR TEMP[1]	390°F	870°F	735°F	795°F
TOTAL CHANGE IN AMBIENT TEMP	974°F EXCEPT 1550°F REMOTE	1176°F	910°F	1044°F
MAXIMUM COOLING AIR TEMP CHANGE IN ONE STEP	95°F ▲ 145°F ▼	145°F ▲ 145°F ▼	150°F ▲ 150°F ▼	150°F ▲ 150°
COOLING AIR TEMP RATE OF CHANGE	≥9°F/MIN	N/A	25°F/MIN ▲ 2.5°F/MIN ▼	N/A
MAXIMUM AMBIENT TEMP CHANGE IN ANY ONE STEP	196°F ▲ 225°F ▼ EXCEPT REMOTE 265°F ▲ 265°F ▼	196°F ▲ 196°F ▼	185°F ▲ 185°F ▼	196°F ▲ 196°F ▼
CHAMBER TEMPERATURE RATE OF CHANGE	≥9°F/MIN	9°F/MIN	3.2°F/MIN	9°F/MIN
NUMBER OF CHANGES IN AMBIENT TEMP	3 EXCEPT REMOTE 9	6	5	5.3
NUMBER OF CHANGES IN COOLING AIR TEMP	5	6	5	5.3
HOURS OF RADAR ON-TIME	21.9	13.5	15.1	14.7
MINUTES OF VIBRATION	240	135	151	147

1 ASSUMING DESIGN REQUIREMENT LIMITS COOLING AIR SUPPLY TEMPERATURE MIN. AT -65°F (-54°C) AND MAX. AT +80°F (27°C)

▼ DENOTES GOING FROM HOT TO COLD

▲ DENOTES GOING FROM COLD TO HOT

In making comparisons between the actual test cycles (i.e., to which the APQ-113/114/144 and the APQ-120 were subjected) and the test cycles defined by MIL-R-26667A, Test Level 3, and MIL-STD-781A, Test Level E, some flexibility exists in interpreting the specifications. Because of variations in the time required for, and the definition of, temperature stabilization, small variations which are a direct result of the time period required for one cycle are not truly significant. For example, the frequency of turning the equipment ON or OFF changes from 5.3 to 5 per day by increasing the stabilization time required by only a few minutes.

The significant conclusions that can be drawn from inspection of this table are given below.

(1) Thermal Shock

The RQT thermal shock to which the APQ-113, -114, and -144 radars were exposed was less severe for LRUs located in the electronics bay and cockpit area but more severe for the radome-located equipment than would have resulted if the RQT

were conducted strictly in accordance with MIL-R-26667A, after which the cycle was patterned.

The APQ-120 received a greater thermal shock during RQT than the cockpit and electronics bay LRUs of the APQ-113/114/144 radars, but it is difficult to compare the radome-located APQ-113/114/144 LRUs with the APQ-120. The total change in cooling air temperature for the APQ-113/114/144 in a 24-hour period of RQT was considerably below both MIL-Specs requirements and that supplied to the APQ-120. The APQ-120 radar was subjected to unusual thermal shocks during the transition from low to high, when cooling air was suddenly drawn from an external source at ambient temperature, resulting in a practically instantaneous change, and during the cold part of the step, when it was reverse-flowed through the equipment. For the cool-down period, the rate of change of cooling air temperature was 2.5°F/minute (1.39°C/minute), the same as the equipment ambient. This was much less than that inferred by the specification of 5°C/minute (9°F/minute) minimum. On a relative basis, this does not represent a great thermal shock. For the heat-up period, however, the rate of change was 25°F/minute (13.9°C/minute) as determined from a typical thermocouple output recording. The fact that cooling air flow was reverse-flowed through the equipment is believed to be an unusual deviation from the intent of the specification and did produce an exceptionally large thermal shock for a number of parts.

(2) Test Chamber Ambient Air

For forced-air-cooled equipment, the ambient temperature and its rate of change impose a much less severe condition than changes in cooling air temperature proper. This is not true for the natural-convection-cooled equipment where part temperatures are directly dependent on chamber ambient temperatures. In comparing the total number of degrees of change in ambient temperature in a 24-hour period, no significant differences exist. The range in temperature excursions for the APQ-113/-114/-144 antenna assembly was much greater than required by the specification and greater than the range over which the APQ-120 was tested.

The APQ-113/144/144 radars were subjected to a much higher maximum ambient temperature than defined by the specifications, or to which the APQ-120 was subjected (i.e., actual 160°F (71°C) vs spec 131°F (55°C) for all except the remote equipment which was subjected to 270°F (132°C).

(3) Thermal Cycles

The APQ-113 was subjected to a greater number of temperature changes in a 24-hour period, but on the basis of number of changes per hour of ON time, which is a more valid comparison, the differences tend to disappear.

(4) Vibration

The APQ-113 vibration was applied for 10 minutes per hour of total test time (i.e., ON plus OFF time). The APQ-120 vibrated for 10 minutes of each hour of radar operation only. For both radar tests, vibration levels and frequencies are within the limits required by MIL-R-26667A for the APQ-113 and MIL-STD-7[illegible]A for the APQ-120. Although different specifications and levels were applied, the acceleration level and frequency at which the APQ-113 was vibrated were also within the limits allowed by MIL-

STD-781B. APQ-113 was vibrated at 0.32G (0.01 inch double amplitude) at 25 Hz and the APQ-120 was vibrated at 2.2G at 57.5 Hz; the total vibration time per 24-hour period was 240 minutes for APQ-113 and 151 minutes for APQ-120.

f. Comparison of APQ-113 RQT with MIL-STD-781

Analysis of the MTBF performance of an equipment must include the basis for its determination, particularly the environmental stress applied. Different applications, testing and use conditions make direct comparisons of equipment reliability performance questionable and perhaps invalid if based on measured MTBF values alone. Use of standardized test conditions, such as MIL-STD-781, provides a sound approach to minimizing the problems of comparison.

Therefore, the following qualitative analysis is provided with the objective of relating the reliability qualification testing actually performed, for the APQ-113 Radar, to MIL-STD-781 requirements and pointing out the anticipated effects on the results due to the identified stress differences. Vibration effects were omitted in this discussion because of their relatively small contribution (≈10%) as compared to the other major stress factors composing the balance of the test cycle (≈90%).

(1) Test Cycle Parameters Affecting Radar Reliability

The MTBF that would be measured by conducting a test fully compliant to the requirements of MIL-STD-781A, Test Level E, would most probably be different from that actually measured for the APQ-113 Radar because of differences in the magnitude and duration of the environmental test stresses applied. In particular, the following selected test parameters are discussed as they could account for significant differences in measured MTBF:

- Frequency of power application
- Frequency of temperature cycles
- Rate of temperature change
- Cooling air ambient temperature

(2) Test Cycle Comparison

The Test Level E cycle contained in MIL-STD-781A is described on page 5-7 and is shown graphically in Figure 72. The reliability qualification test performed on the APQ-113 Radar is shown in Figure 75. In general, the major differences between the MIL-STD-781A Test Level E test and the APQ-113 RQT are as follows:

NOTE: For this discussion, "high" temperature refers to temperatures above 80°F and "low" temperature refers to temperatures below 80°F.

(a) Frequency of Power Applications - MIL-STD-781A, Test Level E, requires that the radar be turned on at the end of the cold portion of the cycle (just before the transient to high temperature) and off at the end of the high temperature. During one 24-hour cycle of the APQ-113 RQT, the radar was turned off for one hour at -65°F, off for one hour at 0°F, and off for 10 minutes at 80°F (refer to Figure 75).

Had the MIL-STD-781A temperature cycle been specified for the APQ-113 Radar, the dwell times would have been 3-1/2 hours at low temperature and 4-1/2 hours at high temperature with 22-minute transient temperature times from high to low and from low to high, resulting in a total cycle time of 9 hours and 44 minutes, each cycle having one power turn on and one turn off. The frequency of power application or removal would thus be two reversals every 9.7 hours, or 5.3 reversals per 24 hours.

The APQ-113 Radar cycle actually experienced six reversals per 24 hours. Although more power reversals per cycle occurred during the APQ-113 Radar test, the power reversals per relevant hour are less. For the MIL-STD-781A cycle, a frequency of 0.34 reversals per relevant hour is obtained as opposed to 0.27 reversals per relevant hour for the APQ-113 RQT cycle. Note that all of the MIL-STD-781A turn-ons are at low temperature.

The quantitative effect on equipment MTBF of the frequency of power turn-on and turn-off is not known, and measurements made during the APQ-113 test do not provide data which allow drawing definite conclusions (no failure was attributed to turn-on and off). However, it is general knowledge that the turning on and off of electronic equipment does impose stress conditions that can lead to component failures. In addition, it is reasonable to presume that the effect of the number of power reversals is linear in that the rate of failures that can be attributed to this stress condition will probably increase in direct proportion to the frequency.

The principal stresses resulting from power application and removal are associated with:

- Current surges in some circuitry
- Heating of components at rates that vary from severe thermal shock in the case of very small, active components to a very slow time rate of change for large components

The temperature at which power is applied and removed must also be considered in attempting to quantize the effect of this test parameter on MTBF; however, there is no known rational way of determining this influence for a complex equipment.

For example, if the equipment is turned off at the end of a stabilization period at elevated temperature (131°F) and at the same time ambient and cooling air temperatures are reduced at the 5°C per minute rate specified in MIL-STD-781A (for ambient to -65°F), then the total temperature change for some active components can be very large. As a specific instance, a semiconductor junction at 125°C at the end of the high temperature portion of the cycle will be at -65°C at the end of the cold part of the cycle, for a total temperature change of 190°C in the junction temperature with a 109°C (i.e., 131 - (-65) = 196°F = 109°C) change in air temperature.

This represents a much more severe stress condition than had the equipment been left on. In this latter case, the junction temperature change would have been about 109°C, or a difference between the two test conditions for this part of 1.8 to 1.

(b) Frequency of Temperature Cycles - Considering the frequency of temperature cycles as an independent variable, exclusive of temperature excursion and rate of change, can be misleading. Some conclusions can be formulated, however, based on the availability of published data.

As a specific example, a recent paper (1972), "A Study of Temperature Cycling as Employed in the Production Acceptance Testing of Electronic Assemblies ('Black Boxes')," by R.W. Burrows of Martin Marietta Corporation concludes (based on data from five companies using MIL-STD-781B) that in order to eliminate incipient defects six cycles are probably adequate for black boxes of about 2000 components, while ten cycles are recommended for 4000 or more components. The further conclusions is reached that, with good parts and packaging technique, temperature cycling is not degrading, up to several hundred cycles.

The APQ-113 RQT 24-hour test cycle included eight changes in ambient temperature for all equipment except the antenna/pedestal/ACU which was subjected to nine. In terms of frequency of individual temperature cycles, all equipment, except the antenna/pedestal/ACU, was subjected to four temperature cycles per 24 hours of test time, or 4.4 temperature cycles per 24 hours of relevant time. The antenna/pedestal/ACU frequency was 4.95 temperature cycles per relevant 24 hours.

Cooling air temperature for all LRUs was changed five times during 24 hours, or 2.5 cycles per 24 hours of test; 2.7 cycles per 24 relevant hours. MIL-STD-781A Test Level E would have required 5.3/2 = 2.65 temperature cycles per 24 hours of test, or 4.3 (i.e., (5.3/2) x (24/14.7) temperature cycles per 24 relevant hours. On either basis, the APQ-113 test exceeded to some degree the requirements of MIL-STD-781A Test Level E in terms of frequency of temperature change on a component basis. However, both the ambient and cooling air temperature limits (amplitude) of the APQ-113 test varied throughout the 24-hour cycle, as shown in Figure 75.

In evaluating the effect of frequency on MTBF, and lacking statistical test data, the logical (and somewhat intuitive) approach would be to presume that failures that are precipitated by the things of which frequency is composed (i.e., time rate of change of temperature and time duration at temperature) would be increased if the frequency were increased, and in a linear fashion. A difficulty in such an approach lies in separating those failures caused by rate of temperature change, by time duration at temperature, by frequency of power turn-on, and by frequency of temperature change.

In the case of the APQ-113 RQT, the difficult problem of quantizing the effect of one parameter of a temperature cycle is further complicated by the fact that the amplitudes (i.e., temperature limits) varied throughout the 24-hour cycle (i.e., no two were the same) and were all different from that which would have been required by MIL-STD-781A Test Level E.

(c) Rate of Temperature Change - When analyzing the effects of the rate of temperature change parameter on equipment MTBF, the primary concern is with the rate of change of temperature of (and temperature profile within) the many components which compose the equipment. Within a complex equipment, component temperatures respond differently to cooling air and ambient transients, and so using the air temperature's rate of change is only an indication of an average effect on parts.

The degree of component stressing associated with temperature transients is known to be a function of the time rate of change of component temperature. Obviously, failures that are caused by such a stress will occur at a faster rate as the time required for a fixed change decreases.

The quantitative effect of rate of temperature change on MTBF of a complex equipment such as the APQ-113 Radar is not readily determined. In addition, beyond the

conclusion that has been reached as a result of the accumulated experience of several organizations involved in Reliability Qualification types of tests, that in general the faster the rate of temperature change, the higher the failure rate (of failures precipitated by this type of stress) little is known.

(d) Cooling Air Temperature and Flow Rate - MIL-STD-781A requires that the cooling air supply temperature and rate of flow be the minimum design flow rate at maximum design temperature during the hot part of the cycle, and the maximum design flow rate at the minimum design temperature during the cold part of the cycle. For the APQ-113 Radar design air flow rate is a unique function of the inlet air temperature; therefore, only one rate is specified for each inlet temperature.

MIL-STD-781 Test Level E as shown in Figure 72 would require cooling air at -65°F for 39% of the total test cycle and air at 80°F* for 61% of the cycle.

Comparison of the APQ-113 cooling air temperature supplied during RQT to the MIL-STD-781 requirement is shown below in terms of percent of the total cycle.

COOLING AIR TEMPERATURE - PERCENT OF CYCLE			
Temperature (°F)	-65	30	80
MIL-STD-781A (%)	39		61
APQ-113* (%)	8.5	54	29

*No air flow - equipment off 8.5% of cycle

(e) Chamber Ambient Temperature - The high chamber ambient temperature for the APQ-113 Radar was equal to, or exceeded, the requirement of MIL-STD-781A, Test Level E (of 131°F) for approximately 64% of the total cycle time. The percent of time spent at a given temperature level is as displayed below.

PERCENT OF TOTAL RQT CYCLE TIME*							
Chamber Temperature (°F)	-65	0	80	131	160	200	270
MIL-STD-781A (%)	39			61			
APQ-113 (%)							
RTM, Sync, Ind. Rec.	13	6	17	29	35		
ACU, Ant., Ant/Ped.	13	6	17			60	4

*Percentages calculated are approximate, and include average transient times.

*Note: The maximum APQ-113 design cooling air temperature for altitude condition is 80°F. For sea level operation, the maximum design temperature is 120°F (with cooling air flow rate increased).

MIL-STD-781A, Test Level E, requires that for approximately 39% of the total cycle time the ambient be at the low temperature of -65°F. The APQ-113 Reliability Qualification Test subjected all LRUs (including the antenna/pedestal/antenna control unit) to low temperatures for 19% of the total test cycle according to the following schedule:

13% at -65°F

6% at 0°F

Seventeen percent of the total cycle time was at an ambient of 80°F.

For the antenna, antenna/pedestal and antenna control LRUs, the high ambient temperature was 200°F for approximately 60% of the total cycle and 270°F for one hour or 4.3% of the cycle. This high ambient is especially significant for the antenna and antenna/pedestal because they are cooled by natural means. In addition, since the total heat dissipation of the ACU is relatively low, heat addition from the ambient has a significant effect on the average cooling air temperature (refer to page 5-12, Cooling Air, and Figure 78), resulting in hotter electronic components internal to the ACU.

3. IN-SERVICE (FLIGHT) ENVIRONMENT

a. Objective

The primary objective of this subsection is to compare a typical environmental flight profile with the environmental conditions during RQT cycle for each of the two radar types. This comparison will be used to correlate the field measured MTBF with that demonstrated in RQT. The relative merits of stress levels and exposure length in RQT versus field encountered conditions are discussed.

b. Summary

- The thermal environment of APQ-120 in flight is milder than that encountered by APQ-113/114/144 based on temperature extremes and the duration of time spent at low and very high temperatures.
- The thermal environment of APQ-120 is more severe in RQT than in flight. The reverse is true for APQ-113/114/144. Neither radars' RQT cycle simulated its actual flight environmental profile very well.
- Although F-4 vibration exposure in flight is more severe than that of F-111, APQ-120 sees levels comparable to APQ-113 by virtue of being vibration isolated versus the latter being hard mounted in the aircraft.
- The RQT vibration environment for both APQ-120 and APQ-113/114/144 radars was periodic at fixed frequency and did not simulate the measured random type encountered in flight.
- No quantitative data was available for field encountered humidity conditions for both radars. Humidity, not controlled during RQT, varied widely, but is considered mild compared to field environments.

c. Thermal Environment

(1) APQ-120

Since no instrumented flight test data defining actual field thermal conditions was available, a computer-simulated thermal analysis of the F-4E aircraft thermal conditioning system was obtained from McDonnell Douglas. The results of this analysis are presented in Table XXVII wherein temperatures for various standard days, altitudes, speeds, and flight conditions are tabulated.

A review of several mission profiles obtained from McDonnell Douglas was made and the flight conditions of speed and altitude were related to the values listed in Table XXVII. As a typical mission example, the aircraft climbs to an altitude of between 30,000 and 40,000 feet, flies at cruise conditions for one hour, descends to 5000 feet for 30 minutes flying at Mach 0.85, climbs to 40,000 feet, and returns to base under cruise conditions. During cruise conditions above 30,000 feet, the data contained in Table XXVII yields an average cooling air temperature of 40°F. This condition accounts for the major part of this mission. A review of other mission profiles yields the same average cooling air temperatures. Cooling air at a temperature much in excess of 40°F is supplied only during short periods of relatively high speed flight or while flying at low altitude.

It can therefore be concluded that for the greatest part of its operational life, APQ-120 will be subjected to the following temperature conditions:

- Radar compartment temperature ambient 78°F (26°C)
- Cooling air supply to radar 40°F (5°C)

The maximum ambient temperature for the Radar compartment is 169°F (76°C) at sea level, Mach 1.1, and maximum radar dissipation. This condition results in a maximum cooling air temperature of 113°F (45°C). The radar is subjected to this condition only occasionally, during supersonic low altitude dash.

Cooling air flow rates vary over a large range for any given inlet air temperature. Under all conditions shown, the actual cooling air flow rate is in excess of design flow by significant margins. This has the effect of reducing the temperature of exhaust air well below both that considered during design, and actually supplied during the Reliability Demonstration Test. It results in a cooling air temperature range that is relatively small, and centered somewhere near normal room ambient temperature.

(2) APQ-113/114/144

Thermal environmental data, obtained from General Dynamics-Fort Worth in the form of a test cycle during which ambient and cooling air temperature levels vary with time, are shown in Figure 79. This figure represents the field environment and is based on the combination of instrumented flight test data and analysis. The relative time durations at each temperature level are representative of relative times during a typical mission.

TABLE XXVII. THERMAL CONDITIONS, F-4E APQ-120 RADAR

DAY	ALTITUDE 1000 FT	MACH NO.	FLIGHT CONDITION	RADAR COMPART. TEMP ° F	RADAR INLET AIR TEMP ° F	RADAR AIR FLOW RATE (LB/MIN)
HOT	SL	.402	MAX END	128	85	24.08
	SL	.53	CRUISE	126	85	29.39
	SL	1.1	MAX PWR	169	113	32.15
	15	.535	MAX END	114	85	24.99
	15	.672	CRUISE	115	85	28.70
	15	1.37	MAX PWR	142	85	30.79
	24.9	.661	MAX END	110	85	24.44
	24.9	.801	CRUISE	112	85	26.65
	24.9	1.61	MAX PWR	141	85	30.33
	25.2	.661	MAX END	79	40	21.41
	25.1	.801	CRUISE	81	40	23.57
	25.2	1.61	MAX PWR	132	70	29.09
	35	.818	MAX END	79	40	19.62
	35	.86	CRUISE	78	40	20.69
	35	1.86	MAX PWR	130	70	28.56
	50	1.0	MAX PWR	107	40	12.40
	50	1.6	MAX PWR	111	40	18.67
STANDARD	SL	.402	MAX END	109	85	29.78
	SL	.53	CRUISE	109	85	34.93
	SL	1.15	MAX PWR	136	85	33.26
	15	.535	MAX END	101	85	29.77
	15	.672	CRUISE	103	85	33.78
	24.9	.661	MAX END	95	80	28.31
	24.9	.801	CRUISE	104	83	31.51
	24.9	1.86	MAX PWR	154	93	28.26
	25.1	.661	MAX END	66	40	24.92
	25.1	1.86	MAX PWR	153	92	28.34
	35	.818	MAX END	67	40	22.44
	35	.86	CRUISE	67	40	23.45
	35	2.2	MAX PWR	158	98	27.83
	55	1.55	MAX PWR	106	40	16.69
	55	1.80	MAX PWR	110	40	18.60
COLD	SL	.402	MAX END	60	63	53.80
	SL	.53	CRUISE	73	76	60.91
	SL	1.26	MAX PWR	95	87	71.02
	15	.535	MAX END	87	78	35.00
	15	.672	CRUISE	84	74	38.98
	24.9	.661	MAX END	61	47	30.43
	24.9	.801	CRUISE	66	51	33.43
	24.9	1.97	MAX PWR	139	62	28.54
	25.1	.661	MAX END	56	40	29.64

MAX END MAXIMUM ENDURANCE
MAX PWR MAXIMUM POWER

In addition, a review was made of temperature sensor output data contained in Technical Report ASD-TR-68-14, Category II Evaluation of an F-111A Aircraft in the Climatic Laboratory and Tropical, Arctic, and Desert Environments. This review revealed that none of the thermal sensors located in the cockpit, radome areas, and in the cooling air supply duct for the forward electronics bay equipment exceeds the Design Specification limits. Nevertheless, in a few instances, the RQT high temperature limits were exceeded when the aircraft was at sea level.

d. Thermal Profile Comparison Flight versus RQT Cycle

Since the forced air temperature exerts predominant influence on equipment's temperature in a forced-air cooled equipment, comparison of flight thermal conditions to RQT profile will be restricted to that aspect only.

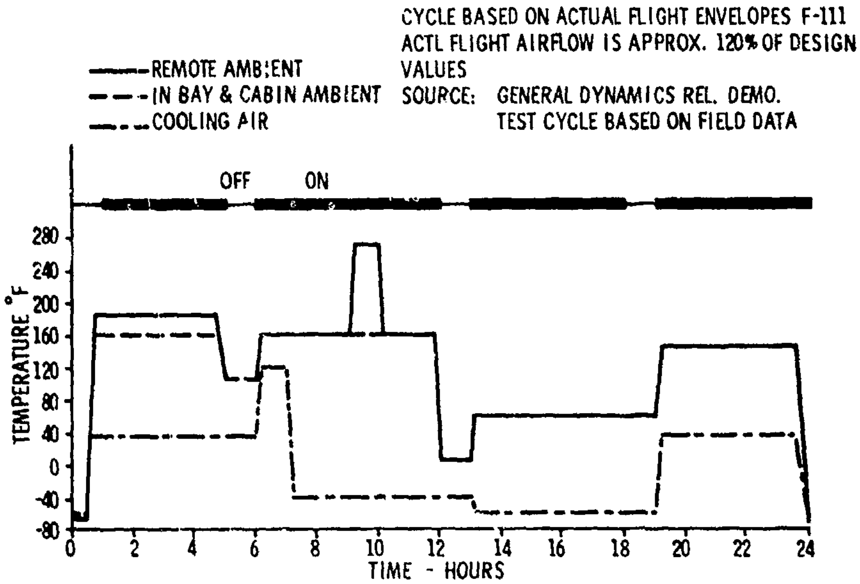


Figure 79. APQ-113 Field Thermal Environment

(1) APQ-120

A graphical comparison of cooling air temperature and the relative duration of radar exposure to each stress level in flight and in RQT is shown in Figure 80. The time base is expressed as a percentage of a typical flight profile as well as that of an RQT cycle. It is apparent that the RQT thermal environment is more severe than the actual flight. In flight, 70% of the time the cooling air temperature is 40°F and during the remaining 30% it is supplied at 85°F (except for a short period ≈3% at 115°F). By contrast, in RQT 30% of the time the forced air is as supplied at -30°F or below and during 58% at 85°F.

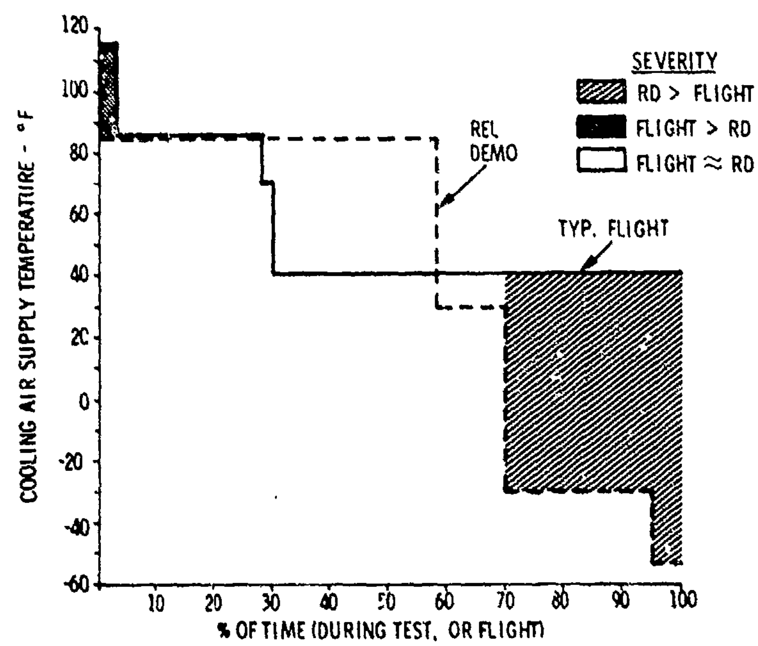


Figure 80. APQ-120 Reliability Qualification vs In-Flight Cooling Air Temperature

(2) APQ-113/114/144

A similar comparison of forced air temperature versus percentage of time is portrayed graphically in Figure 81. It is apparent that a typical flight environment is more severe than the RQT cycle. Forced air temperature during flight is at or below -46°F for 55% of the time versus only 12% in RQT. Although the cooling air temperature in RQT exceeds the flight environment 25% of the time, the temperature of +85°F is not as detrimental to parts reliability as is the 120°F cooling air received 5% of the time (i.e., 35°F above the RQT level).

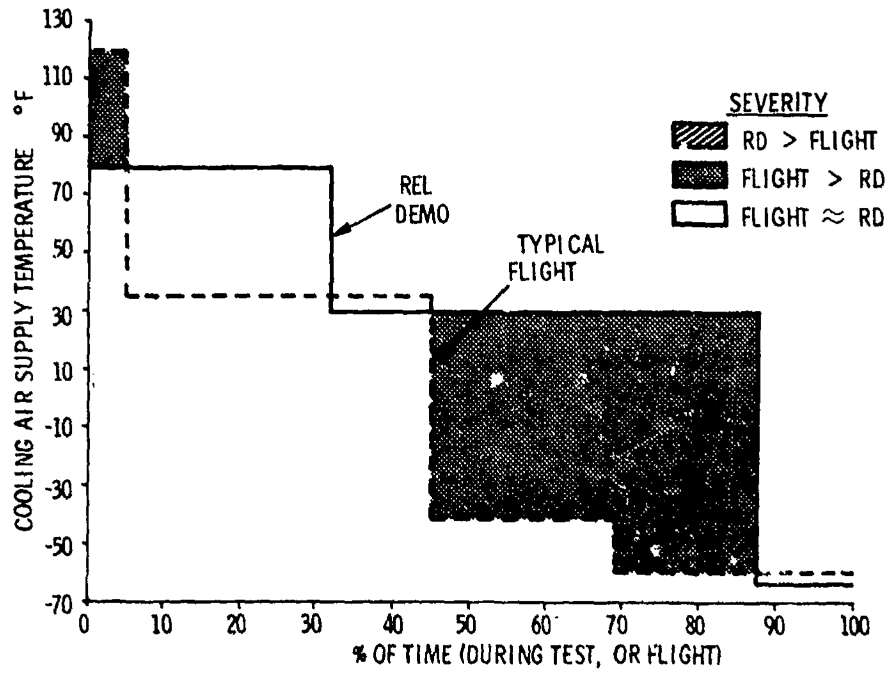


Figure 81. Reliability Qualification - Flight, APQ-113 Equipment, Cooling Air Temperature

e. Vibration Environment

(1) Flight Conditions

(a) APQ-120 - Data used for determining the aircraft vibration environment of equipment located in the nose of the F-4E aircraft is shown in Figures 82 and 83, from which Figure 84 was calculated.

- Normal flight condition data was based on RF-4C aircraft data in which a relatively small, vibration-isolated radar is installed. Lacking data

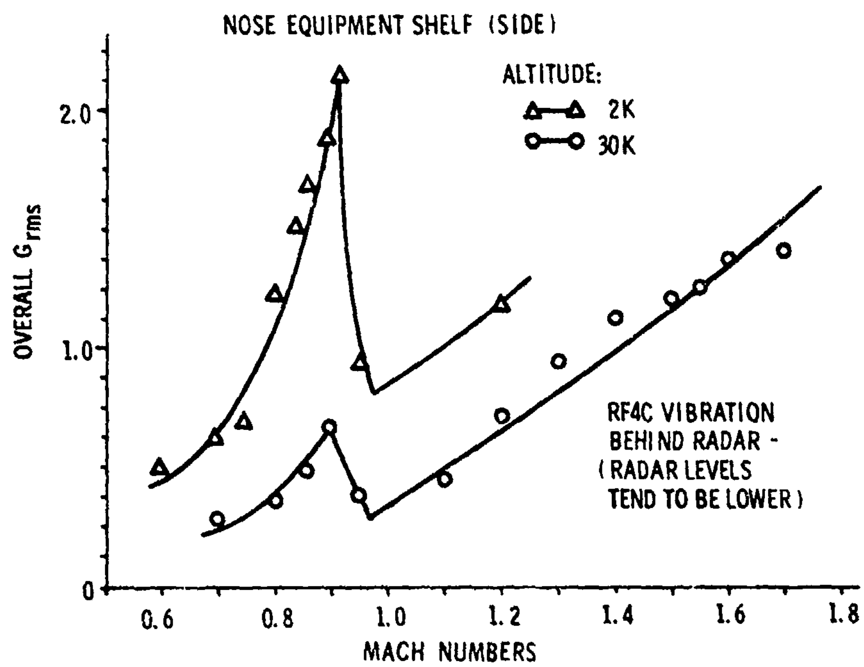


Figure 82. RF-4C Overall Vertical Vibration, G_{rms} vs Air Speed

for the F-4E containing an AN/APQ-120 Radar, it is presumed that these data are representative within acceptable limits. Note that the AN/APQ-120 radar is also vibration-isolated, and the measured flight vibration levels are low when compared with qualification test levels.

- Gunfire vibration data was obtained for the F-4E with an M61 Vulcan 20 mm gun mounted in the nose, under the AN/APQ-120 Radar.

For normal flight conditions, the data obtained from accelerometers mounted on the RF-4C radar mount provide the following representative vibration conditions:

Mach Number, M	Altitude, h (ft)	Dynamic Pressure, q (psf)	Acceleration G_{rms}
0.85	2,000	1005	1.2
0.90*	2,000	1130	1.5
1.80	30,000	1800**	2.5

* at M = 0.9 there is an oscillating shock aft of the chin. Its effect is shown in Figures 82 and 84.
** Higher q flight in the F-4E is likely - up to 2500 psf.

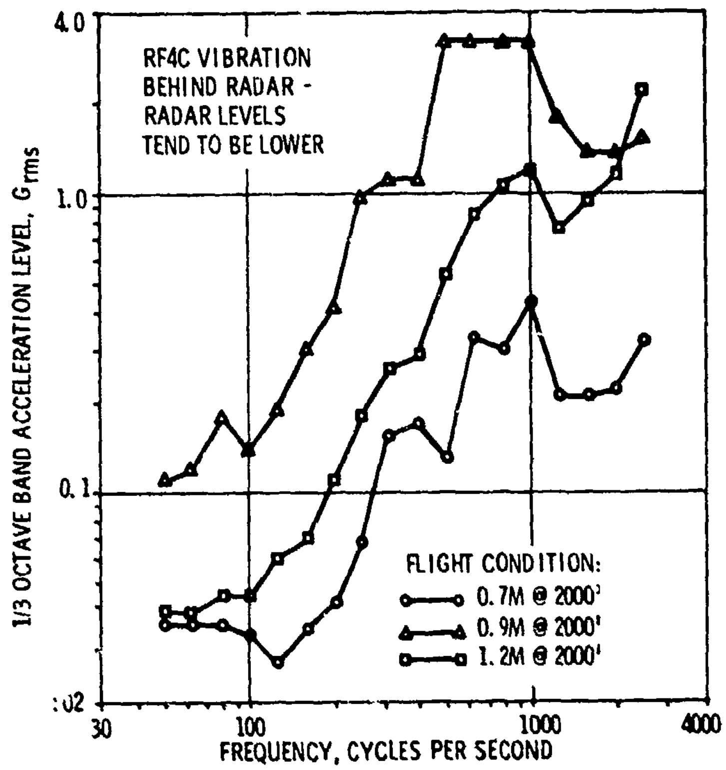


Figure 83. RF-4C Overall Vertical Vibration, G_{rms} vs Frequency

Note that the characteristic of the vibration environment of the aircraft is random, with a series of peaks in the spectrum. (Figure 83)

Since both the RF-4C and the F-4E have very similar structure, and both radars are isolated, it is safe to assume that normal flight vibration levels in the nose area will be about the same. The one notable difference, the lack of a "chin" on the F-4E, will probably result in a lower level of vibration, near M = 0.9, because of the reduction in aerodynamic disturbances.

Vibration resulting from firing the M61 nose-mounted 20 mm gun installed in the F-4E produces an input to the AN/APQ-120 Radar (at the aircraft side of the isolators) that consists of a fundamental signal of essentially 100 Hz sinusoidal vibration, and associated harmonics. The harmonics from 300 Hz to 800 Hz are the important components of the vibration, and each harmonic shows an acceleration level of about 17G RMS. The overall level for six harmonics is thus $G = \sqrt{6} \times 17 = 41.7G$ rms. The fundamental and other harmonics are negligible. This level is of course attenuated to a much lower level by the vibration isolators before it reaches the radar.

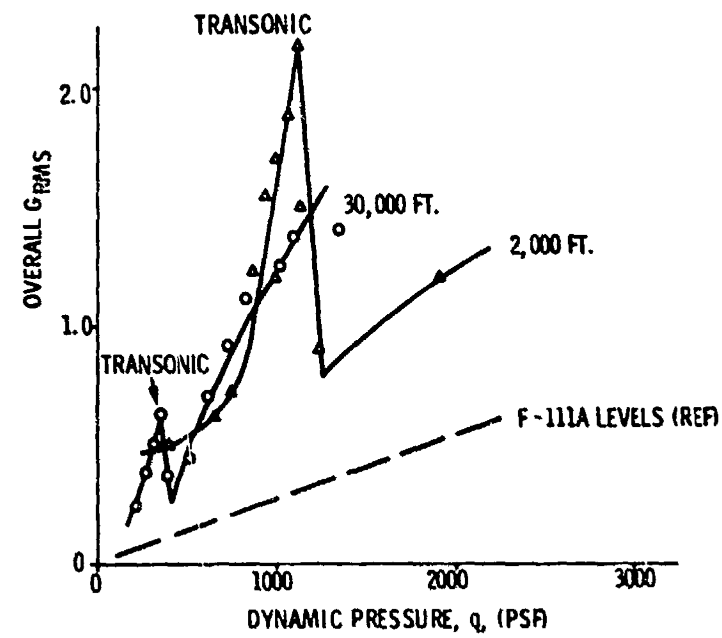


Figure 84. RF-4C Overall Vertical Vibration, G_{rms} vs Dynamic Pressure

In addition to structural vibration in the nose compartment, there will be some acoustic vibration at 100 Hz and associated harmonics,as high as 150 db,resulting from gunfire.

(b) APQ-113/114/144 - The data used for defining the flight vibration environment in the F-111 were obtained from two sources:

- Normal flight vibration data from flight test reports for airplane number 75, issued by General Dynamics, Fort Worth.
- Gunfire vibration data from flight test reports for airplane number 5, equipped with a single gun firing at a nominal rate of 6000 rounds per minute (100 rounds/second).

The data apply equally well to the APQ-113, -114, -144 Radars. These three radars are practically identical from a structural standpoint; all three are hard mounted and installed in the same locations on the F-111 aircraft; the antenna assembly in the radome, the RTM (MRT), and Synchronizer in the forward electronics bay, the Indicator/Recorder LRU in the cockpit. A review of vibration data in the cockpit area shows levels to be, in general, significantly lower than in the nose locations.

Normal flight vibration data on the Forward Bay Rack is summarized in Figure 85 and Table XXVIII. It is generally low-level (0.64 G_{rms} maximum), varies linearly with dynamic pressure, is wide-band random in nature, and the spectral shape is largest around 500 Hz.

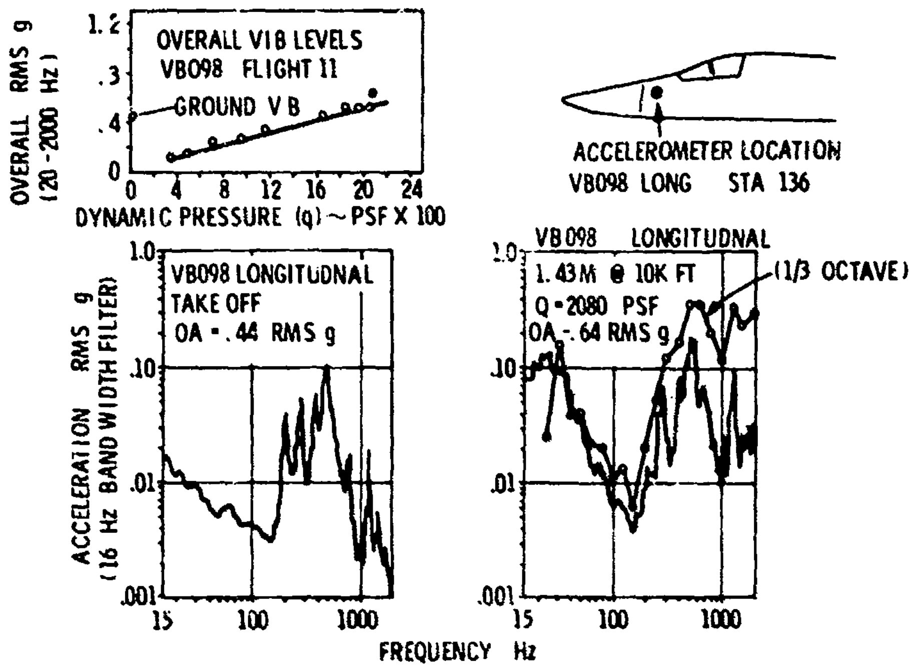


Figure 85. F-111A Vibration Measurements, Forward Electronics Bay Equipment Rack

TABLE XXVIII. APQ-113 FLIGHT VIBRATION LEVELS

FLIGHT CONDITION			OVERALL VIBRATION LEVELS (10-2000 Hz) RMS g — FWD ELECTRONICS BAY EQUIP RACK FRAME		
			VERT	LAT	LONG
MACH	ALT	q	VB096	VB097	VB098
T.O.	-	-	.35	.30	.44
.94	16000	710	.23	.22	24
1.10	14200	960	.23	.22	.26
1.40	15000	1650	.41	.40	.45
1.43	10000	2060	.51	.45	.64
.90	22500	490	.14	.13	15
.79	24600	340	.11	13	.11
1.19	15800	1160	.27	.29	.34
1.46	14000	1550	.45	.44	.52
1.45	12100	1960	.45	.44	52
1.44	10500	2090	.46	.45	55
1.42	10230	2050	.48	.44	.52

FLIGHT CONDITION			FWD ELECTRONICS BAY AFT BULKHEAD			FWD ELECTRONICS BAY LOWER LONGERON		
			VERT	LAT	LONG	VERT	LAT	LONG
MACH	ALT.	q	VB084	VB085	VB086	VB015	VB016	VB017
T.O.			.06	.04	.13	.15	.04	.02
40	1700	200	.04	.02	.06	.26	11	04
1.05	12300	1020	.47	.34	39	1.05	.90	56
1.19	10600	1420	49	.41	.49	1.35	1.29	97
1.26	10500	1540	56	.43	.52	1.51	1.63	1.19
1.30	10400	1690	55	.45	.56	1.51	1.72	1.23
1.33	11000	1600	60	.43	.52	1.36	1.91	1.10
1.32	11000	1800	.63	43	60	1.51	1.72	1.19
.95	16000	710	22	.22	.26	95	73	.33
1.40	10400	1930	71	54	65	1.65	1.94	1.41
87	23000	506	35	34	39	.99	86	.66

Unlike normal flight vibration which is random, the vibration resulting from gunfire consists of a series of harmonics of the gun firing rate, superimposed over normal flight vibration.

The single gun used in the F-111A is mounted about 35 feet from the nose, resulting in low levels of vibration in the radome locations. Gunfire vibration levels are substantially greater than normal flight vibration, but less than qualification vibration levels in most cases. A worst case vibration spectrum obtained during gunfire is included in Figure 86. Typical levels are between 25% and 50% of these worst case levels.

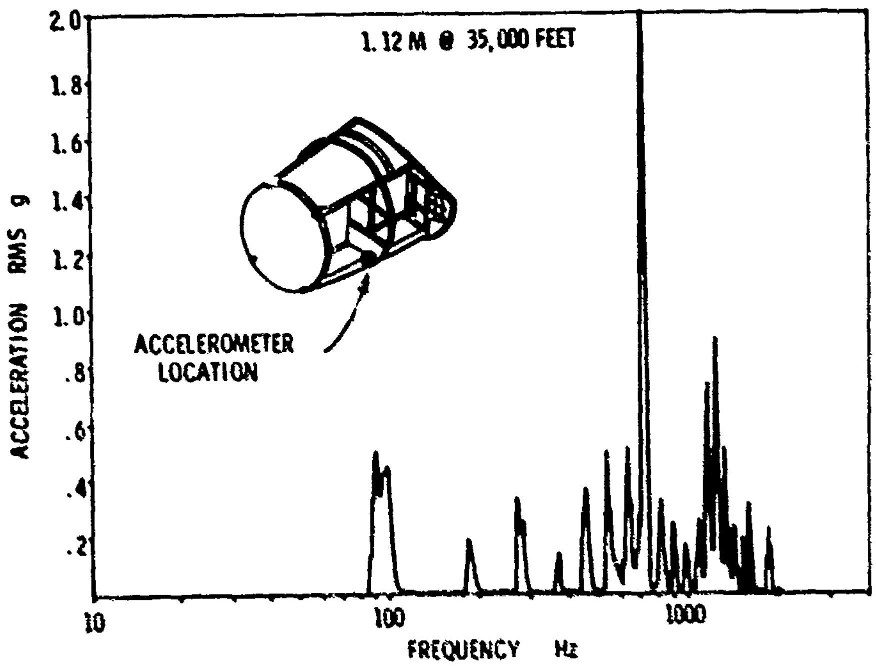


Figure 86. Flight Test Gun Vibration Data, F-111A Weapons Bay, Forward Electronics Bay, Lower Shelf, Vertical

(2) Flight versus RQT Cycle - APQ-120 and APQ-113/114/144

Table XXIX summarizes the vibration environment in flight and RQT to provide comparisons. Conclusions are drawn in the table but basically:

1) The F-4 normal flight vibration levels are two to three times as severe as the F-111 at equivalent locations.

2) The F-4 gunfire levels are much more severe at the radar location than the F-111 because of the proximity of the gun to the radar.

3) The Reliability demonstration test of the F-4 radar applied more severe accelerations than the F-111, and properly so.

TABLE XXIX. VIBRATION COMPARISON

			F-111	F-4	COMPARISON OR COMMENT
FLIGHT	NO GUNFIRE	CHARACTER	WIDE-BAND RANDOM	WIDE BAND RANDOM	SIMILAR
		SPECTRAL SHAPE	PEAK CONTENT AROUND 500 cps	PEAK CONTENT AROUND 500 cps	SIMILAR
		LEVEL @ RADAR	LOW- 0.64G_{RMS} OVERALL	LOW- 1.6G_{RMS} OVERALL	F-4 TWO TO THREE TIMES AS SEVERE AS F-111
		TRANSONIC REGION	NO EFFECT	2.2G_{RMS} OVERALL	RF4C HAS OSCILLATING SHOCK WAVE AFT OF "CHIN". LOWER LEVELS EXPECTED IN F-4E
		DEPENDENCE ON DYNAMIC PRESSURE, q	G_{RMS} VARIES LINEARLY WITH q	G_{RMS} INCREASES WITH q	SIMILAR
	GUNFIRE	CHARACTER	PERIODIC AT BASIC FIRING RATE AND ITS HARMONICS	PERIODIC AT BASIC FIRING RATE AND ITS HARMONICS	SIMILAR
		SPECTRAL SHAPE	100 TO 1500 cps HARMONICS PEAKING AT 700 cps	400 TO 800 cps HARMONICS OF NEARLY EQUAL AMPLITUDE	DIFFERENT
		LEVEL @ RADAR	2-4G_{RMS} @ EACH HARMONIC	17G_{RMS} AT EACH HARMONIC	F-4 MUCH MORE SEVERE DUE TO SHORTER DISTANCE BETWEEN GUN MOUNT & RADAR
RELIABILITY DEMONSTRATION		CHARACTER	PERIODIC	PERIODIC	SAME
		SPECTRAL SHAPE (FREQUENCY)	25 cps	57.5 cps	DIFFERENT
		LEVEL @ RADAR	±.32G ± .01 IN. DA	±2.2G ± .013 IN. DA	F-4 IS 7 TIMES AS SEVERE IN VIBRATORY ACCELERATION
		TIME	10 MIN. EACH HOUR	10 MIN. EACH HOUR OF POWER ON TIME	

4) The levels applied during the Reliability Qualification tests were:

a) For F-111 - About one-third the highest flight level.

b) For F-4 - About equal to the highest flight level.

5) The vibration applied in both demonstration tests was periodic, and not a good simulation of the measured, random flight environment.

f. Humidity Environment

(1) General

The humidity design criteria for the APQ-113/114/144 Attack Radar and the APQ-120 Fire Control Radar were defined by the Qualification Test Requirements. Formal humidity testing was limited to the Qualification Test. The test cycles specified in both MIL-R-26667 and MIL-STD-781 do not include controlled humidity levels; however, the ambient air and the cooling air supplied during these tests obviously contain water vapor

to some degree. The quantity of water vapor in the cooling and ambient air during RQT is a function of:

1) Relative humidity of the ambient in the vicinity of the test chamber.

2) The temperature cycle to which the air is subjected.

3) The design of the air conditioning equipment, including such factors as the degree of sealing of the test chamber and associated air ducts, provisions for water drainage from cooling coils, and source of cooling air.

Humidity effects can be classified as long term or short term. The predominant long term problem is associated with the slow absorption of moisture, either liquid or vapor by various materials, which may lead to eventual degradation and/or failure. Short term effects are generally caused by liquid water, for example, contained as small droplets in cooling air, or condensation from relatively high humidity air on surfaces at lower temperatures than the air. As an example of a typical condition during which condensation could present a significant problem, consider an electronics equipment installed in an aircraft flying at high altitude, with the electronics stabilized at a low temperature. A fairly rapid descent to a low altitude, where air is much warmer, and at a high relative humidity, will result in condensation of water on the cold surfaces.

The quantity of water accumulated is a function of the rate of change of temperature of the surfaces on which the water is condensing. A thin, light weight printed wiring board might develop a thin layer of moisture before its temperature rises to near that of the surrounding air. A large transformer on the other hand could cause a substantial quantity of water to accumulate because of its higher thermal inertia and resultant slower temperature rise.

(2) RQT

Humidity was not a controlled RQT environment. Although humidity was not measured in RQT, it is known to have varied widely during the period of testing of APQ-113/114/144, and is assumed to have varied during the APQ-120 test.

As a result, data is not available which can be used to quantize the Reliability Demonstration Test environments. A qualitative conclusion can be drawn, however, that humidity conditions were normally mild during those tests, when compared with the field environment. Thus it is also safe to conclude that most problems that are associated with humidity in field deployment would not be discovered during the RQT as defined by MIL-STD-781 and MIL-R-26667, and as actually performed.

(3) First Article Qualification Tests

The humidity qualification requirements for the F-111 Radar were as follows:

1) Humidity Test - The equipment under test was placed in an environmental test chamber in a manner similar to service use and subjected to ten of the steps described below:

Step 1 - The chamber temperature was raised to 50°C (122°F) during a two hour period, with relative humidity in excess of 95°.

Step 2 - The chamber temperature was maintained at 50°C (122°F) with relative humidity in excess of 95% for 6 hours.

Step 3 - The chamber temperature was reduced to 38°C (100°F) over a 16 hour period, with relative humidity above 85%.

Within one hour, following 240 hours exposure to the cycles described, the equipment was inspected and tested electrically. The equipment was not operated electrically during exposure to the humidity test environment.

2) Humidity in Cooling Air Test - The forced air cooled equipment was subjected to a 50-hour test during which cooling air at room ambient temperature with a relative humidity of 100% and containing 39 grains of free water per pound was supplied. The flow rate of the cooling air was approximately 125% of minimum airflow required. The equipment was electrically operated for the last 45 hours of this test, and functional testing was performed every 10 hours.

The APQ-113 LRUs were subjected to these tests without failures. The APQ-114 and -144 LRUs were not tested, but the test requirements were met by similarity with the APQ-113 LRUs.

The design specification for the APQ-120 radar stated that the equipment should be designed to operate satisfactorily in an environment of 100% relative humidity, and air temperature up to 71°C (160°F) including conditions wherein condensation takes place in and on the equipment. The First Article Qualification Test specification conditions were:

1) The equipment to be stabilized at -62°C (-80°F) and held at this temperature for 2 hours. The chamber ambient then to be increased to 85°C (185°F), stabilized and held at this temperature for 2 hours. The chamber ambient then reduced to room temperature. Humidity not to be controlled during this step.

2) The chamber temperature to be increased to 71°C (160°F) during a 2-hour period, with relative humidity maintained in excess of 95%.

3) The chamber ambient maintained at the conditions of 71°C (160°F) temperature, and relative humidity in excess of 95°F for six hours.

4) For all except unpressurized, forced air cooled (from the aircraft supply) equipment, the chamber ambient to be reduced at a uniform rate to 38°C. The unpressurized, forced air cooled equipment, the ambient to be reduced at a uniform rate to -54°C (-65°F). Steps 2, 3, and 4 were repeated until a total of ten cycles was completed. The equipment was then to be returned to room ambient conditions, and after removal of excess moisture by momentarily inverting each unit, was immediately checked for satisfactory operation.

(4) Field Conditions

The field humidity environment is comprised of at least those listed below either alone or in some combinations, which vary with time.

1) Liquid water contained in the cooling air supplied to the equipment.

2) Liquid water contained in the equipment ambient, for example, in the form of rain.

3) High relative humidity of the cooling air and of the equipment ambient. This condition would occur most often at low altitude.

4) Conditions under which water condenses from supplied cooling air or from the equipment ambient, on components and other surfaces, forming a film of water on these surfaces, and in an extreme case, an accumulation of water which drips from the surfaces.

These humidity conditions may occur with large fluctuations in ambient and cooling air temperatures and with the equipment either operating or non-operating.

Both radars in the field experienced humidity related problems. "ASD/ENVA Report APQ-120 Reliability Review" by Col. Bright et al describes the catastrophic effects of frost on APQ-120. APQ-113 experienced condensation problems in the Synchronizer and RTM LRUs after deployment in South East Asia (high relative humidity air on the ground causing condensing on the cold parts after return from high altitude flights). Both problems were solved by a redesign of the LRUs.

Another detrimental condition associated with humidity, but also time related, is the reaction of air pollutants (e.g., aircraft exhaust fumes), contamination, and corrosion on the equipment. First Article or Reliability Qualification Test do not attempt to simulate the effects of prolonged equipment exposure - a real-life field conditions - to these environments.

SECTION VI

FIELD AND PLATFORM PERFORMANCE ANALYSIS

A. INTRODUCTION

This section describes the field and platform* performance of three radars (APQ-120, -113, -114) which are installed aboard four high-performance aircraft (F-4E, F-111A, F-111E, FB-111A) presently in the USAF inventory. The data for the study is based on 66-1 reports and has been extracted from airframe manufacturers' reports, subcontractors' test logs, and USAF personnel interviews at the Flight Line, Base Shop, and Depot level, and covers the time span of one year (December 1970 through November 1971). Data covering the entire contract delivery span was also utilized whenever available and applicable.

The analysis of this data is summarized in tabular and graphical format, comparing various reliability parameters of the respective radars. This section is divided into several subsections related to the investigation of particular field reliability aspects. Each analytical subsection is introduced by its objective and summary of findings, followed by detailed data analysis.

B. SUMMARY

This section of the study covers the following aspects/overviews of the reliability of each radar after its shipment from the factory:

- Evaluation of field reliability performance in terms of $\underline{R}$ rate, $\underline{M}$ rate, abort rate, and flight hours per maintenance man-hours
- Relationship of field achieved reliability to specified requirements and comparison with other avionic equipments installed aboard high performance aircraft
- Comparison of factory demonstrated reliability with subsequent platform and field performance
- Analysis of the measurement result differences between RQT demonstrated reliability and 66-1 reported field performance
- Analysis of experienced EEE parts reliability and distribution of platform and field failures

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*The term "platform" used throughout this section denotes radar operation from the time of its receipt by the airframe contractor until the delivery of the entire aircraft to the USAF.

C. FINDINGS/CONCLUSIONS

- F-111 radars (APQ-113/114) exhibited a 2.5 to 4.0 time higher field R rate than the F-4E radar (APQ-120) as reported June-Nov. 1971 (RCS 6 LOG K261).

- R to M rate ratio of the radars studied is approximately 3:1.

- Mean Time Between Aborts (MTBA) is highest for APQ-114 followed by APQ-120 and APQ-113. Abort rate data is believed to be more influenced by equipment function than by failure rate.

- Man-Hour per Maintenance Action figure is lowest for APQ-120 followed by APQ-114 and APQ-113. The APQ-113 in the F-111E exhibits a 50% greater man-hour consumption per maintenance action than the APQ-113 in the F-111A. Maintenance personnal familiarity, aircraft field deployment length, base manning levels, and equipment utilization appear to be the most influencing factors.

- Generally it was concluded for the equipments studied that:

  a) High reliability parts will upgrade field reliability by a factor of not less than four.

  b) Reliability Evaluation Tests have a ten-fold effect on field reliability.

  c) Environmental preconditioning has a minimum of a five-fold effect on platform reliability.

- Field data shows no reliability growth on APQ-113/114 and APQ-120 during field deployment.

- The F-111 aircraft avionics equipments exhibit an R rate equal to 20% of factory demonstrated MTBF. Similar pattern is observed for avionics equipments aboard other high performance aircraft.

- Of five avionics equipments surveyed, only the APQ-120 and APQ-109 had field reported R rates that exceeded the contract required minimum acceptable MTBF, suggesting that the reliability requirements had been underspecified. The APQ-120 MTBF requirement is 10% of the requirement imposed on other radars when normalized to parts count complexity.

- With the application of appropriate modifier factors, the 66-1 USAF Data System reported MTBF, hereafter referred to as R rate, can be a useful indicator of equipment's true field MTBF.

- The differences between field R rate and factory demonstrated MTBF can be explained through the application of modifier factors accounting for differences in RQT and flight environmental profiles, ON-time record keeping, and failure diagnostic capability.

- The percent of unverified ("serviceable") failures can severely penalize the field MTBF if defectives are reintroduced.

- The percent of unverified failures is significantly lower in RQT than in the field. Primary influencing factors are: (1) AGE capability - simulation of environments and interfaces; (2) motivation to pass the test; and (3) troubleshooting regimentation.

- APQ-113/114 platform performance shows a decrease of failures with each successive test level - on receipt through flight - reflecting preconditioning in the factory, to the flight environment. APQ-120 platform performance shows an increase in failures per equipment from on receipt to in-flight attributed to not having been exposed to similar preconditioning.

- The estimated 15:1 cost of failures difference between radars at platform level is attributed to the environmental factory preconditioning of the APQ-113/114.

- Electrical, Electronic, and Electromechanical (EEE) part failure rates (replacement rates) at platform and field are lower by approximately one order of magnitude on APQ-113/114 than on APQ-120, which is attributed to differences in program parts screening.

- Contractor performed reliability predictions reflecting failure rates consistent with the quality of material are a good indicator of field performance. Minor disparities could be accounted for by the fact that predictions are based on part-count failure rate techniques and ignore workmanship and in-service induced failures.

- Field part replacement rates on APQ-113/114 did not single out any one device. The platform replacement rate nevertheless identified transistors and specialty devices as constituting 50% of all replacement. This may be accounted for by the difference in environmental profiles between LRU burn-in and flight.

- Approximately 50% of APQ-120 field replacements are mechanical parts and diodes. Diodes are not screened in APQ-120 and mechanical parts possibly indicate a wear-out mode that was not detected during the short RQT (30 hours per equipment) nor in the First Article Qualification Test.

- Approximately 42% of APQ-120 platform replacements are modules and specialty devices, reflecting the effects of first environmental exposure on these items (encapsulated items).

D. RECOMMENDATIONS

- For improved reliability measurement consistency and accuracy, establish and introduce conversion factors into the 66-1 MTBF to account for actual equipment ON-hours vs flight hours.

- Distribute the 66-1 data to all subcontractors to provide them with visibility of field experienced reliability.

- To achieve a higher field reliability, the specified RQT environmental cycle should be consistent with MIL-E-5400, MIL-STD-781, and adjusted only upward when field environments require it, with equal weighting for cold and hot environments and performance measurements at each extreme and during temperature transitioning.

- Require environmental preconditioning - equivalent to in-service environment - for 100% of equipment to detect pattern failures and reduce platform/field infant mortality failures. Preconditioning should consist of X cycles with the last Y cycles failure-free.

- Increase BITE capacity and make it capable of detecting interface malfunctions to reduce the percentage of unverified failures. Furthermore, provide environmental troubleshooting capability at the Depot and Base maintenance shops.

- Limit the "repair" at Base level on sophisticated equipment to replacement of "plug-in" assemblies. Confirm each failure via the "double substitution" technique.

- Do not allow equipment which has not demonstrated its specified reliability or passed the Environmental Qualification Test to be deployed in the field ("PASS BEFORE FLY").

- Require material quality to be consistent with TX, ER or MIL-M-38510 to maximize performance and minimize costs. Do not allow substitution of lower grade material in field repairs.

E. FIELD RELIABILITY COMPARISON

1. OBJECTIVES

The primary objectives of this subsection are the assessments and comparisons of field reliability of the respective radars as reported in 66-1 and expressed in terms of:

- Field reliability expressed in Mean Flight Hours Between Failures, hereafter referred to as 66-1 R rate.

- Field maintenance rate expressed in Mean Flight Hours Between Maintenance Actions, hereafter referred to as 66-1 M rate.

- Flight hours per maintenance man-hour (FH/MMH).

- Maintenance man-hours per maintenance action.

- Abort rate

Having established these values, comparisons are made between the respective radars in the form of figure of merit ratios (i.e., values normalized to the APQ-120 radar performance). This data will be used to establish trends and to support various analyses in other subsections and sections.

2. SUMMARY

Information extracted from 66-1 data system - summarized in Table XXX - indicates that APQ-114 reliability is superior to other radars which were subjects of this study. It is followed by APQ-113(E), APQ-113(A), and APQ-120, except that both APQ-113s exhibit a lower Mean Time Between Aborts rate than APQ-120. All four radars show that the R rate/M rate ratio is approximately 3:1.

TABLE XXX. 66-1 DATA, APQ-120 VERSUS APQ-113/114

PERFORMANCE ATTRIBUTE	APQ-120	APQ-113(A) *		APQ-113(E) *		APQ-114	
	VALUE	VALUE	FIGURE OF MERIT ** RATIO	VALUE	FIGURE OF MERIT ** RATIO	VALUE	FIGURE OF MERIT ** RATIO
R RATE (HOURS)	11	26	2.5	33	3.0	46	4.0
M RATE (HOURS)	4	8	2.0	13	3.0	16	4.0
FH/MMH	0.4	0.62	1.5	0.69	1.7	1.48	3.6
MTB ABORTS (HOURS)	1,718	1,227	0.7	1,461	0.8	3,317	2.0

DATA SOURCE: RCS 6 LOG K261

TIME PERIOD: JUN - NOV 1971

*(A) DENOTES INSTALLATION ABOARD F-111-A; (E) ABOARD F-111-E

** FIGURE OF MERIT RATIO = $\frac{\text{APQ X VALUE}}{\text{APQ 120 VALUE}}$

3. DATA ANALYSIS

The data source for this investigation was RCS 6 Log K261 covering the time period of June - November 1971. The maintenance man-hours - used in the computation of FH/MMH - included scheduled and unscheduled maintenance in the Field, Shop and Depot. Abort rate was computed using both ground and flight aborts caused by these radars. No attempt was made to validate the accuracy of RCS 6 Log K261 data.

Table XXX summarizes the performance attributes of each radar and shows their respective figure of merit ratios. A peculiar element is the performance difference between the F-111A and F-111E radars - which are identical APQ-113 radars - except for the fact that the "A's" (installed aboard F-111A) are two years older. The reported difference was considered of no consequence and not radar attributable by the Nellis AFB (where the majority of "A's" are located) Logistics personnel because the radar LRUs were used interchangeably between the A and E aircrafts, and were serviced by one base maintenance shop. As will be seen later, the $\underline{R}$ rate normalization will bring these two more in line.

Although APQ-113 shows higher $\underline{R}$ rate and $\underline{M}$ rate figures than those of APQ-120, its Mean Time Between Aborts figure is lower. This leads to a conclusion that the Abort rate is primarily affected by the radar's function and systems integration, more than by its failure rate (e.g., the F-111 uses its radar almost constantly, with other aircraft equipments also depending upon it, while the F-4E uses the radar only for certain mission events and is not integrated with other equipments.

Analysis of Figure 87 reveals good correlation between the MMH/FH ratio and the $\underline{M}$ rate figure of merit ratio for APQ-113(A) vs APQ-120 and APQ-114 vs APQ-120 (e.g., $0.52 \approx 1/2.0$ and $0.22 \approx 1/4.0$). However, the MMH/FH ratio for the APQ-113(E) vs APQ-120 does not track their $\underline{M}$ rate figure of merit ratio (e.g., $0.50 \neq 1/3$).

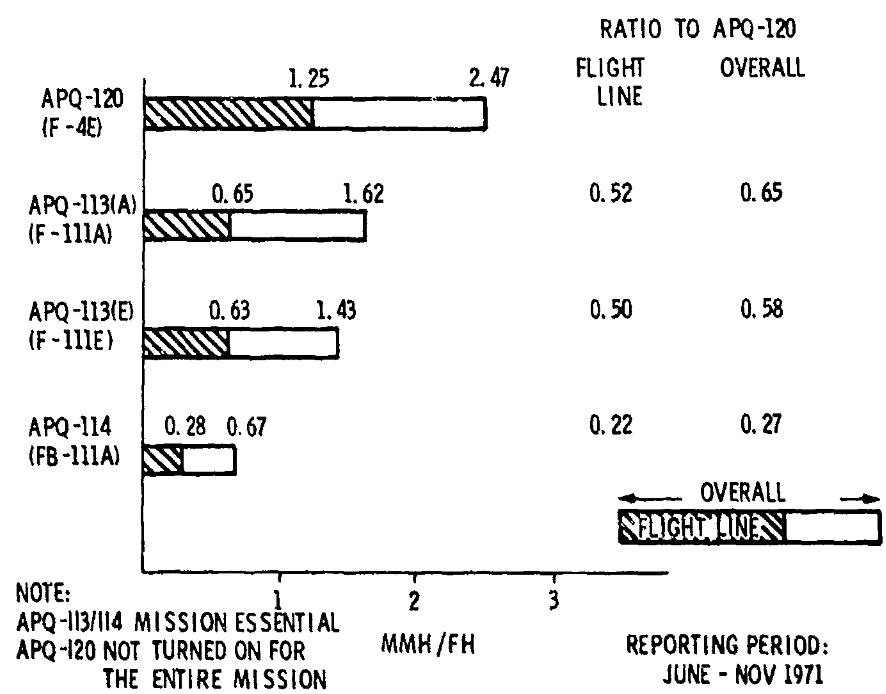

Figure 87. Maintenance Man-Hours per Flight Hour, APQ-120 vs APQ-113/114

Discussion of this variation with Air Force logistics personnel indicated that many facets impact maintenance, e.g., equipment utilization, maintenance approach, manpower availability, work hours reporting/charging, spares availability, training, familiarity with AGE and prime equipments. The most direct explanation for the disparity in

ratios between the F-111A and F-111E radars may be the fact that the majority of the F-111E, as of the date of the source data, have been at Upper Heyford, UK, for a relatively short period of time, and the higher maintenance man-hours may reflect learning growth.

This disparity can also be gleaned from Table XXXI which presents maintenance hour statistics for the six-month period between June and November 1971. It is of interest to note that APQ-120 requires the lowest number of man-hours per maintenance action, probably reflecting the benefits of the longer learning curve and the ease or accessibility of repair due to more partitioning (e.g., 19 LRUs versus 8 LRUs in APQ-113). However, a striking contrast of MMH/MA between APQ-114 and APQ-113, and among the APQ-113 - F-111A vs F-111E - which are essentially the same radars - points out the drastic effects of maintenance approaches and warrants further study.

TABLE XXXI. MAINTENANCE MAN-HOURS PER MAINTENANCE ACTION, APQ-120 VS APQ-113/114

RADAR	UNSCHEDULED MAINTENANCE MANHOURS ($X10^3$)	NUMBER OF MAINTENANCE ACTIONS	MMH / MA	RATIO TO APQ-120
APQ-120	255	28400	9.0	1.0
APQ-113(A)	24	1739	13.7	1.5
APQ-113(E)	14.7	758	19.4	2.2
APQ-114	6.7	637	10.5	1.2

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F. FIELD RELIABILITY PERFORMANCE VERSUS SPECIFIED REQUIREMENT-AVIONICS

1. OBJECTIVES

The primary objective of this subsection is to compare the achieved field reliability versus specified requirement of representative avionic equipments aboard several high performance aircraft to determine how the radars fit a "typical" avionics performance.

2. SUMMARY

In general, the field reliability of the avionic equipments studied, installed aboard high performance aircraft, exhibit 20% (between 15% and 40%) of their specified and

subsequently demonstrated MTBF requirement. The M rate is usually 1/2 to 1/3 of the field experienced R rate. APQ-120 is the only radar, of the five surveyed, meeting or exceeding in the field its specified MTBF. However, the specified MTBF for the APQ-120 is only 10% of that specified for the APQ-113 for an equivalent functional complexity. This leads one to the conclusion that the APQ-120 reliability requirement was much less challenging or that its field reliability measurement was unrealistic.

3. DATA ANALYSIS

To determine if the four subject radars fit into a typical performance of avionic equipments aboard a high performance aircraft, a survey was made of the reliability record of F-4D, F-4E, F-111A, F-111E, FB-111 and A-7E avionics equipments. These equipments and their field reliability performance are tabulated in Table XXXII.

The F-4D offers a direct comparison to the F-4E, being in most cases identical equipment, while the A-7E provides a comparison to deployed avionics equipment of latest design and technology. It was generally concluded that the R rate reported by the 66-1 data system for the F-111, F-4D and A-7E avionics equipment is at approximately 20% of specified reliability requirement at 90% confidence, and the MTBMA at approxi-

TABLE XXXII. AVIONICS PERFORMANCE

	EQUIPMENT	REQUIREMENT MTBF @ 90%	CHALLENGE COMPLEXITY	66-1 MTBF			66-1 MTBMA		
				F-111A	F-111E	FB-111	F-111A	F-111E	FB-111
F-111	FLIGHT CONTROL COMPUTER	300	17K	60	27	105	27	15	6
F-111	FORWARD LOOKING RADAR	137	10.7K	26	33	46	8	13	16
F-111	CENTRAL COMPUTER	560	1K	129	162	146	78	84	95
F-111	BOMB/NAV SET	243	5.7K	24	29	-	10	17	-
F-111	AVOIDANCE RADAR	108	4K/CH	46	35	45	12	16	15
F-111	ALTIMETER	500	8K/CH	75	60	130	35	30	45
F-111	LEAD OPT SIGHT	300	.8K	201	318	1050	36	78	195
				F-4E	F-4D		F-4E	F-4D	
F-4	LEAD OPT SIGHT	300	.55K	362	271		33	56	
F-4	FIRE CONTROL RADAR	9	13.5K	10	9		3	2	
F-4	NAVIGATIONAL SYS. COMP.	320		69	49		35	26	
F-4	ATTITUDE REF COMPUTER	173		67	54		26	21	
F-4	BOMB NAV COMPUTER	250		173	109		37	24	
F-4	INERTIAL NAVIGATION	180		44	34		12	10	
F-4	INTEGRATED ELEC CENTRAL	50	5K	30	22		17	12	
				A-7E			A-7E		
A-7E	BOMB NAV COMP	650	6.3K	63			11		
A-7E	FORWARD LOOKING RADAR	125	7.9K	19			8		
A-7E	INERTIAL MEASUREMENT SET	125	2.2K	46			4		
A-7E	AIR DATA COMPUTER	600	11K	82			42		
A-7E	DOPPLER RADAR	50	7.4K	42			5		
A-7E	HEAD UP DISPLAY	50	2.6K	54			4		

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mately 10% of the same requirement. In the majority of the cases, these equipments did pass a Reliability Test successfully, either the first time or in subsequent tests, indicative that they possessed inherent reliability capability and that the specified reliability requirements were realistic.

It is of interest to note that only the APQ-120 and -109, among the five radars (APQ-109, -113, -114, -120, -126) aboard these aircraft, exhibit in the field a slightly higher than specified MTBF at 90% confidence level. This is associated with an MTBF requirement that is approximately 10% as demanding when normalized for parts count complexity to the other radars. This observation may lead one to a conclusion that the reliability requirement for APQ-120 was not as challenging and consequently did not require employment of high reliability disciplines by the contractor, with resultant low field MTBF. The observation that APQ-120 R rate exceeded its MTBF requirements is further contrasted by the fact that APQ-120's RQT demonstrated values were below its R rate and also below its specified MTBF value.

The few equipments that did not fit directly the 20% R rate pattern were equipments with either low use when calculated against flying hours, or equipments with high inheritance/maturity; nevertheless, their M rates generally fit the overall pattern. At the present, with the available information, it appears that the 66-1 failure/maintenance categorization may also create this disparity. In some equipment a malfunction could be corrected by adjustment of controls, minor repair, calibration, and hence be classified as maintenance action per current 66-1 data system reporting procedure. In other equipments, where the number of adjustment controls has been minimized, malfunctions would require replacements, thereby increasing the number of 66-1 reportable failures. From this data it is concluded that the M rate is directly proportional to the R rate which indicates that improvements in reliability can have a direct impact on both the "Failure" actions and the "Maintenance" actions. When relating failures and maintenance actions, the same precautions discussed on pages 61 and 62 would apply.

G. RQT TO FIELD RELIABILITY CORRELATION

1. OBJECTIVE

The primary objective of this subsection is to identify and quantify the basic reliability factors which account for the differences existing between the factory demonstrated reliability performance and the reliability reported and achieved in the field environments, for the equipments studied, so that the effect of reliability disciplines can be evaluated and reliability qualification testing can be improved, ultimately to result in improved equipment field reliability.

2. SUMMARY

Based on the analysis of APQ-113 and APQ-120 flight-profile and RQT environments, RQT and field reliability performances, surveys of field repair adequacy and quality, several factors, which possibly account for over 60% of the differences, were derived and are listed in Table XXXIII.

The disparity between measured test and field MTBF is attributed to factors such as time base, failure definition and accounting and stress level differences. The test measurement is found more precise than the field for the readily identifiable factors such as time base and failure accounting as the test is conducted under ideal factory conditions. RQT may not, however, adequately forecast field reliability performance if the test stresses applied are not representative of the field environments to be encountered.

TABLE XXXIII. RQT/FIELD RELIABILITY COMPARISON FACTORS

RELIABILITY FACTORS	DEFINITION	NEED
ENVIRONMENT:		
(1) FIELD TOTAL K_S	$\frac{\text{MTBF (HRS) RQT}}{\text{66-1 MTBF (HRS) ADJUSTED}}$	RQT IS NOT REPRESENTATIVE OF THE TOTAL FIELD ENVIRONMENT WHICH INCLUDES FLIGHT ENV., HANDLING, FACILITIES, PERSONNEL, ETC.
(2) FLIGHT PROFILE K_p (PART OF K_S)	FLIGHT PROFILE/RQT TIME AT TEMP. EXTREMES	INCLUDED IN K_S. COMPARISON OF FLIGHT PROFILE WITH RQT CYCLE SHOWS SIGNIFICANT DIFFERENCES.
MEASUREMENT:		
(1) TIME K_t	RATIO OF AVIONICS POWER TIME TO REPORTED FLIGHT HOURS	TO ADJUST 66-1 TIME BASE FROM FLIGHT HOURS TO EQUIPMENT OPERATING TIME. TAXI, CHECK OUT AND MAINTENANCE TIME IS NOT INCLUDED.
(2) FAILURE REPORTING K_r	$\frac{\text{66-1 REPORTED FAILURE BASE}}{\text{66-1 FAILURE BASE-SERVICEABLE/UNVERIFIED}}$	TO ADJUST THE 66-1 FAILURE BASE BY REMOVING ALL SERVICEABLE/UNVERIFIED FAILURES. CAUSE IS LIMITED FIELD DIAGNOSTIC CAPABILITY.

3. DATA ANALYSIS

Using the data available and the K_t and K_r factors, identified in Table XXXIII and quantified in this subsection, the 66-1 data was adjusted upward in Table XXXIV to account for imprecision in the field data reporting system, permitting a gross estimation of the degree (K_S) to which reliability qualification testing simulates the complete field environment.

TABLE XXXIV. RQT/FIELD MTBF SIMULATION RATIOS

RADAR	RQT MTBF (HR) @ 90% LCL (A)	66-1 REPORTED R RATE (HRS) (B)	66-1 MODIFIER FACTORS (C) = $K_t \cdot K_r$	66-1 ADJUSTED MTBF (HRS) D = (B) (C)	MTBF SIMULATION RQT/FIELD K_S = A/D
APQ-120 F4E	4.3	11	(1.1) (1.42)	17.2	.25/1*
APQ-113 F-111A	152	26	(1.5) (1.8)	70.2	2.2/1**
APQ-113 F-111E	152	33	(1.5) (1.55)	76.5	2.0/1**
APQ-114 FB-111A	145	45	(1.5) (1.55)	109.0	1.3/1**

* INDICATES RQT 4 TIMES MORE SEVERE THAN FIELD ENVIRONMENT.
** INDICATES RQT 1.3 - 2.2 TIMES LESS SEVERE THAN FIELD ENVIRONMENT.

a. ON-Hours Factor, K_t

The K_t modifier of RQT demonstrated, to field experienced, reliability d els with power ON-time accumulation. The value of this modifier varies on these radars from less than 1 to almost 2. This alone double the values of the $\underline{R}$ rate reported in 66-1 (6-Log-K-261) report. On the F-4E, at Nellis AFB, for instance, the APQ-120 radar is utilized on less than 90% of flights and, when utilized, is not left on during the entire mission; on the F-111 A/E, the APQ-113 is turned on immediately and is left on during the entire mission, including taxi time. Also to consider are the maintenance shop ON-hours which constitute a substantial share of ON-hours over and above flight hours. Similarly, flight line "ON-EQUIPMENT" testing adds to the total ON-hours.

Because the Elapsed Time Indicator (ETI) recording is not a 66-1 requirement, even though each radar is equipped with an ETI (on the APQ-113/114 all LRUs have one), the actual ON hour statistics are not available. Nevertheless, at Nellis AFB, the 474th TFW Maintenance Shop had maintained individual LRU records, by serial number, with ETI recorded both in and out of shop, that showed the total power ON-time was 1.5 to 1.8 times the total flight time for the APQ-113 (most of the F-111As are located at Nellis AFB). For the APQ-120, a previous Reliability study had assessed this factor at 1.1.

b. Diagnostic Capability Factor, K_r

Another modifier factor developed, K_r, accounts for the high percentage of serviceable (i.e., unconfirmed failures) items which are attributed to the degree of diagnostic capability and quality of field troubleshooting/failure detection activity. K_r is based on the following methodology supported by field experience.

Flight MTBF, reported in 66-1, is computed by using the following equation:

$$\text{MTBF} = \frac{\text{Flight Hours}}{\text{Quantity of A/C removals - Quantity of serviceables}} \tag{32}$$

where the term "serviceables" applies to those removed items which could not be duplicated or confirmed as "hard failures" - e.g., glitches, or intermittents, environmentally induced problems or interface problems.

Now, the $\underline{R}$ rate number as reported in RCS 6-Log-K-261 is lower than that computed by using the raw numbers of flight hours, quantity of removals and quantity of "serviceables" reported in RCS 5-Log-K-261. This difference can be partially attributed to the established computerized methods and data controls, which require a "match" between a removal action and a serviceable action, before the "censorship" (subtraction) is executed. For the purposes of this study, it was considered essential that all serviceable actions be considered and counted. Table XXXV presents the data and establishes a value for a K_r' factor.

Another influence for the understated $\underline{R}$ rate number is the "apparent" repair at the LRU level, accomplished through replacement by a spare subassembly, with subsequent diagnosis of the removed subassembly as "serviceable" at the lower echelon

TABLE XXXV. 66-1 REPORTED MTBF 6-LOG-K-261 VS 5-LOG-K-261, APQ-120 VERSUS APQ-113/114

RADAR	A FLIGHT HOURS	5-LOG K 261 B # REMOVALS (T-1)	C # SERVICEABLES	D COMPUTED MTBF $\frac{A}{(B-C)}$	E 6-LOG K 261 REPORTED MTBF	K_r' $\frac{D}{E}$
APQ-120	203270	22750	7710	13.5	11	1.23
APQ-113(A)	26020	1106	305	32.5	26	1.23
APQ-113(E)	20200	704	131	35.0	33	1.06
APQ-114	17487	425	74	49.8	46	1.08

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repair level. The error in this case is compounded, first by not "censoring-out" a "serviceable" unit from the removals count; second, this is indicative that the original cause of the malfunction has not been corrected and "exists" either elsewhere in the LRU or in the "serviceable-diagnosed" subassembly. In practice, this item will be returned to service-use and cause another malfunction in the future, which will possibly be scored again as a failure.

To account for these discrepancies, a modifier factor, K_r'' has been established. The K_r'' factors for both radars were computed from the field and factory repair data and are tabulated in Table XXXVI.

TABLE XXXVI. PERCENT SERVICEABLE DISTRIBUTION IN FIELD & FACTORY R&R, APQ-120 VS APQ-113/114

RADAR	PERCENT SERVICEABLE: LRUS BASE + DEPOT (A)	LRUS R&R AT FACTORY (B)	ASSEMBLIES BASE + DEPOT (C)	ASSEMBLIES R&R AT FACTORY (D)	A+B+C+D	K_r'' $\frac{1-A}{1-(A+B+C+D)}$
APQ-120	31.2	-	9.6	-	40.8	1.16
APQ-113(A)	24.0	2.4	1.5	20.2	48.1	1.46
APQ-113(E)	17.5	3.3	.6	22.0	43.4	1.46
APQ-114	18.0	4.3	.6	20.7	43.6	1.46

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Using the values of K_r' and K_r'' for the respective radars the field repair/factory modifier factor K_r can be computed using the following expression:

$$K_r = K_r' \cdot K_r'' \quad (33)$$

It is of interest to note that a close correlation is obtained for the APQ-120, APQ-113(E), and APQ-114 radars where the values of K_r are 1.42, 1.55, 1.58 respectively.

The value of K_r for the APQ-113(A) is 1.8, thus modifying its R rate to a value matching the R rate of APQ-113(E) (e.g., 47 to 51 hours respectively versus the previously reported R rate in the 6-Log-K-261 report of 26 and 33 hours), narrowing the reported 27% difference to a mere 8%. Also to be noted is that the reported Nellis AFB (F-111A) serviceable rate is 37%, as extracted from the 474th TFW TAC K18 reports, which surpasses the rates published in the AFLC reports for the entire APQ-113 - F-111A - force.

Further analysis of the "serviceable" or "unverified" pattern is portrayed in Figure 88. The high percentage of "serviceable" (unverified) items in the field compares closely with the "platform" and "factory" percentage. This is explained by the fact that as complexity increases, the diagnostic accuracy decreases, and the additional aircraft interfaces complicate the verification process of a failure.

In RQT however, the percentage of "unverified" failures drops down drastically. APQ-113/114, for instance, experiences a 43.4% unconfirmed malfunction rate in the field as compared to 6% in RQT. The same comparison for the APQ-120 contrasts a 40.8% figure in the field with 5% in RQT.

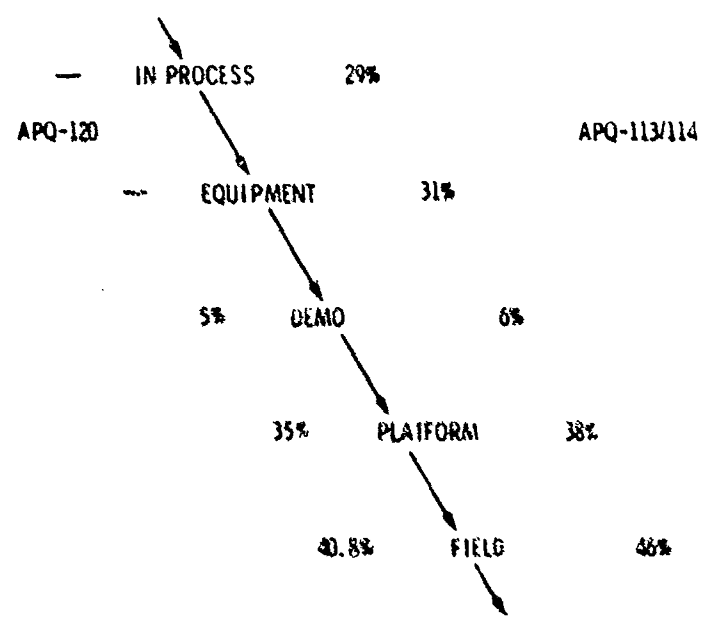

Figure 88. Percent Unverified Failures Flow (Serviceables)

Based on personal observations by GE personnel of field maintenance "modus operandi", the RQT to field disparity can be ascribed to the following:

- Attention to detail and controlled conditions in the factory due to "fear of failure" atmosphere (i.e., "pass-the-test" motivation).
- Lack of adequate AGE, simulating aircraft interfaces and environments, in field and depot maintenance shops.
- Skill, diagnostic specialization differences between factory trained technicians and service personnel.
- On-the-spot consultation with Design Engineering personnel to assist in the diagnosis during RQT.
- Differences in diagnostic procedures, wherein minimum use of "double-substitution method"* was practiced by field personnel to verify a flight-reported malfunction.

c. Environmental Profile Factor, K_p

Environmental differences between RQT and flight conditions were found to exist but are difficult to quantify due to unavailability of failure data related to particular environments. For example, in the case of the APQ-113/114, the predominant flight environment is cold (Figure 81), since during 55% of flight time, the temperatures range between -35°F and -60°F. In contrast, during the RQT environment, only 12% of the time is spent below -35°F. For the APQ-120, the opposite condition occurs (Figure 80), wherein 30% of the RQT was below -35°F, but the flight environment was never lower than +40°F.

d. Other Factors

Other factors that affect the disparity between field and factory demonstrated reliability but which for lack of quantitative data have not been computed are:

- Handling differences of equipment during maintenance and repair in the field as compared to factory environment.
- Quality of repairs by field and depot personnel when compared to the requirements and skill of factory experienced operators and associated quality standards.
- Test equipment capability and availability at various maintenance echelons in the field is lower than in the factory.
- Repairs in the field are often made with substitute parts of lower quality/reliability.

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*A "double-substitution method" referred to herein requires replacement of the malfunctioning item with another working item. Upon disappearance of malfunction symptoms, the original item is reintroduced into the system to see if the trouble recurs.

H. FACTORY, PLATFORM AND FIELD RELIABILITY COMPARISONS

1. OBJECTIVE

The primary objective of this subsection is to analyze and compare each radar's reliability performance in Reliability Qualification Test, at platform and in the field.

2. SUMMARY

APQ-113/114 shows a close correlation, after normalization with the applicable K factors, to field and platform performance, between prediction, RQT, platform and field. The platform somewhat higher failure rate can be attributed to the new environment, handling and interfaces, while the field performance differences reflect factors which have not been addressed, e.g., field handling, part substitution, field workmanship, and the remainder of environmental factors.

APQ-120 reflects a relationship between RQT and platform similar to the APQ-113/114 but at a failure rate which is ten times greater than predicted. Field performance reflects a 5:1 ratio to the APQ-113/114.

The estimated cost of failures difference between radars, at platform level, is attributed to the environmental factory preconditioning of the APQ-113/114.

The radar field experience to date indicates that field reliability growth of equipment, once deployed, was not achieved on any radar, notwithstandinc ECP activity.

3. DATA ANALYSIS

Reliability performance of APQ-113 and APQ-120 was compared at significant performance levels such as factory Reliability Qualification Test, platform (i.e., Aircraft Avionics Integration Tests), and field deployment. Data from the last RQT was used in these comparisons to reflect the comparative maturity of the equipments (i.e., after all redesigns. A comparison of the 66-1 reported field reliability versus predicted values was made, to check on the accuracy of reliability prediction methodologies.

Since the two radars differ in parts count (10,704 in APQ-113 versus 13,553 in APQ-120), the data were normalized to "failures per million part hours" to assure a common base. The time period covered in this investigation is from December 1970 through November 1971 and represents 203,000 flight hours and 3300 platform ON hours for the APQ-120; 53,500 flight hours and 4100 platform ON hours for the APQ-113.

Previously developed K factors were applied to the reported field rates. Results of this survey are summarized in Figure 89 and the reliability performance ratios between the respective radars, at each level of operation (i.e., factory RQT, platform, field), are also shown. It can be noted that quite a disparity exists between the RQT demonstrated values of the two radars. The disparity in RQT performance (30:1) is attributable to the lower quality grade of parts (≈4:1) and the lack of RET for the APQ-120 (~10:1).

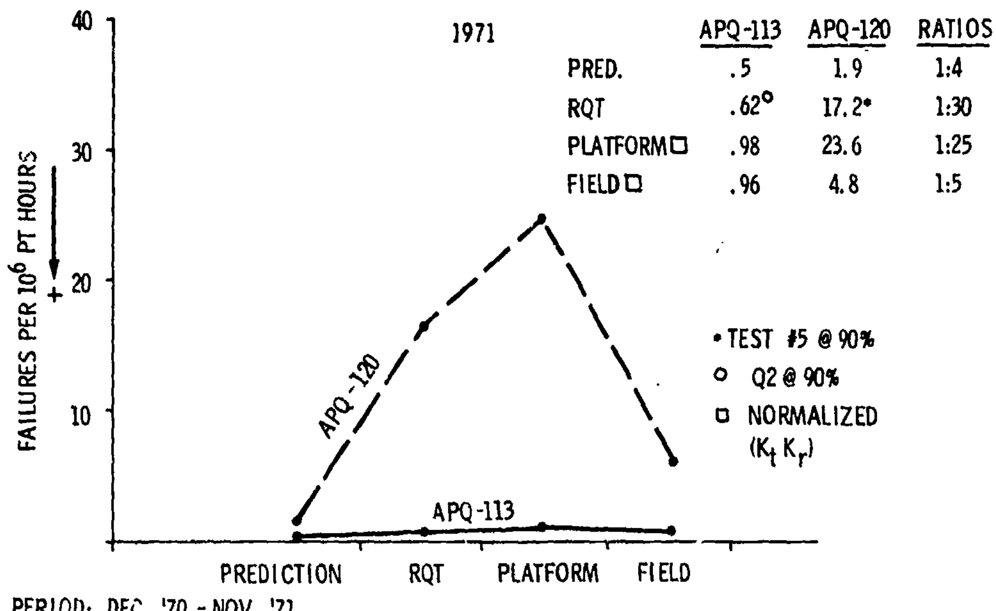

Figure 89. Failure Rates, Factory to Field, Failures per 10^6 Part Hours, F-111A/E APQ-113 and F-4E APQ-120

Despite the normalization with K factor, the RQT experienced failure rates do not track one for one the extrapolated field values. This can be attributed to the remaining unquantified differences, previously described in Subsection G.

The divergence (25:1) in platform failure rates of the two radars is attributed to a compounding effect of parts quality, environmental factory screening and reliability maturity of APQ-113 gained through the RET. The platform performance for each radar does not follow its RQT performance and the difference can be attributed to new environment, new interfaces, and looser control over failure incidents. In RQT each radar had a low percentage of relevant failures whereas at platform all failures attributed to the radar were considered relevant.

The field reliability, normalized to each radar's parts count, differs by a ratio of 5:1 between the APQ-120 and APQ-113/114. This divergence is again attributed to the differences in reliability disciplines (e.g., parts quality, RET) which affected the platform performance. However, the field performance divergence (5:1) is smaller than the platform divergence (25:1), explained through the nullification of LRU environmental screening effects, after initial flight environment exposure.

For the APQ-120, its field performance is also four times better than its RQT performance. This is due to additional unquantized severity factors present in the APQ-120 RQT, such as the thermal shock during transition from cold to hot, and environmental profile differences.

Another analysis of platform and field reliability was made utilizing performance data accumulated over the entire period of field deployment. Comparative performance, reflecting averages for 1968-1971, at platform is shown in Figure 90, displaying failures per aircraft processed.

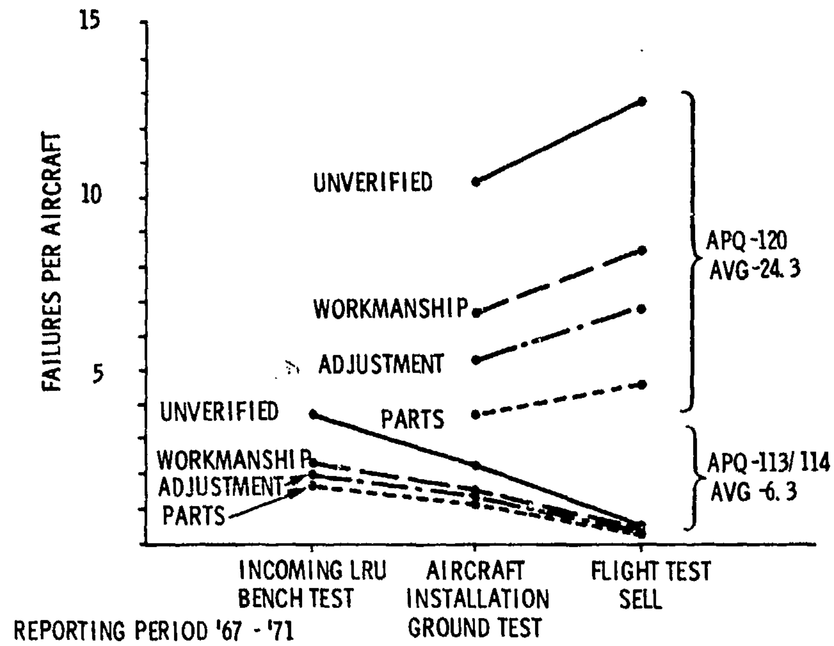

Figure 90. Platform Failure Distribution, APQ-120 vs APQ-113/114

To explain the difference between APQ-120 and APQ-113/114 performance at platform test, the respective platform processing methods need definition. The APQ-120 is received at platform as an equipment, installed in the aircraft for a ground checkout, and then flight tested and sold. The APQ-113/114 is received at platform not as an equipment but as LRUs, tested at General Dynamics incoming as LRUs and installed in an aircraft by LRU to complete an equipment for ground test and flight test and Air Force sell.

The APQ-113/114 shows initial failures at incoming and bench LRU test and a minor quantity at aircraft ground test when the LRUs are first integrated as an equipment with other avionics systems. Additional features during flight/sell are insignificant and indicate that the APQ-113/114 equipment was ready to be subjected to the aircraft flight environment.

In contrast to this, the APQ-120 performance reflects a significant addition of failures when subjected to the aircraft flight environment. This essentially shows that the APQ-120 equipment had not been previously environmentally conditioned to meet the aircraft flight environment.

Finally, the failures per aircraft attributable to the radars as experienced by the two prime contractors are compared and related in terms of costs (Figure 91). It was decided not to include unverified failures in the comparison, because this may "penalize" the radars, as the "unverified" could be caused by the interfaces or other unknown factors.

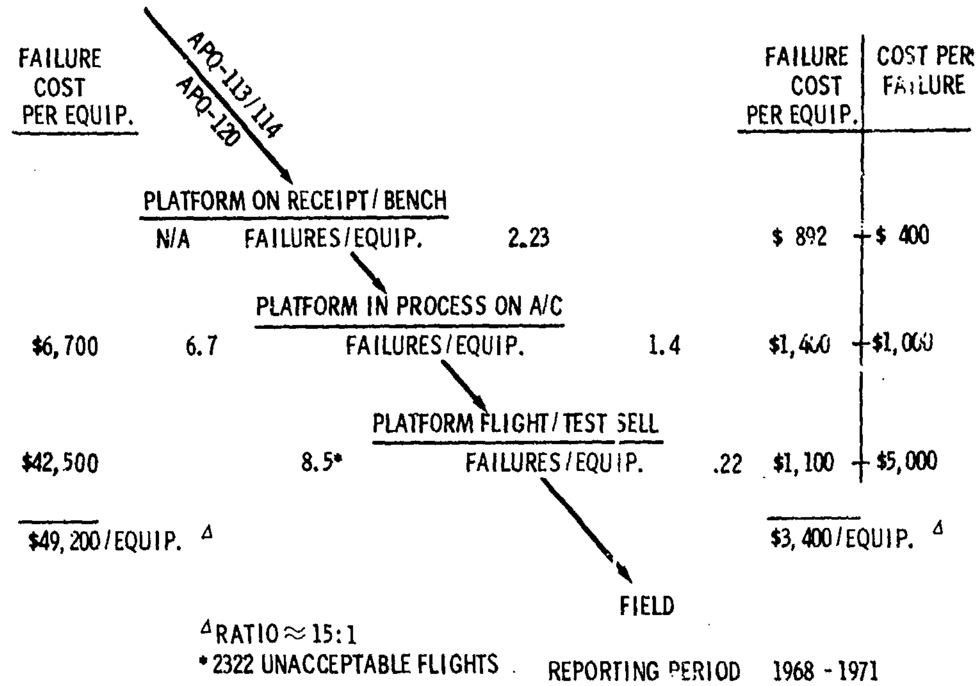

Figure 91. Platform Failure Cost
APQ-120 F-4E vs APQ-113/114 F-111

Using estimated platform failure cost figures which were obtained through discussions with airframe manufacturers - i.e., $400 for an "on-receipt" failure, $1000 for an "in-airframe" failure, and $5000 for a "flight" failure, cost comparisons for platform integration are made between the two radars. It is estimated on this basis that integrating the APQ-120 into the F-4E aircraft avionics was more expensive by an approximately 15:1 ratio, excluding the cost of factory preconditioning the APQ-113.

The field reliability over the reported deployment cycle for both radars is shown in Figure 92. It is apparent that while the $\overline{R}$ rate ratio of 4:1 between the two radars is maintained, neither one shows reliability growth of any significance during the reporting period 1967-1971.

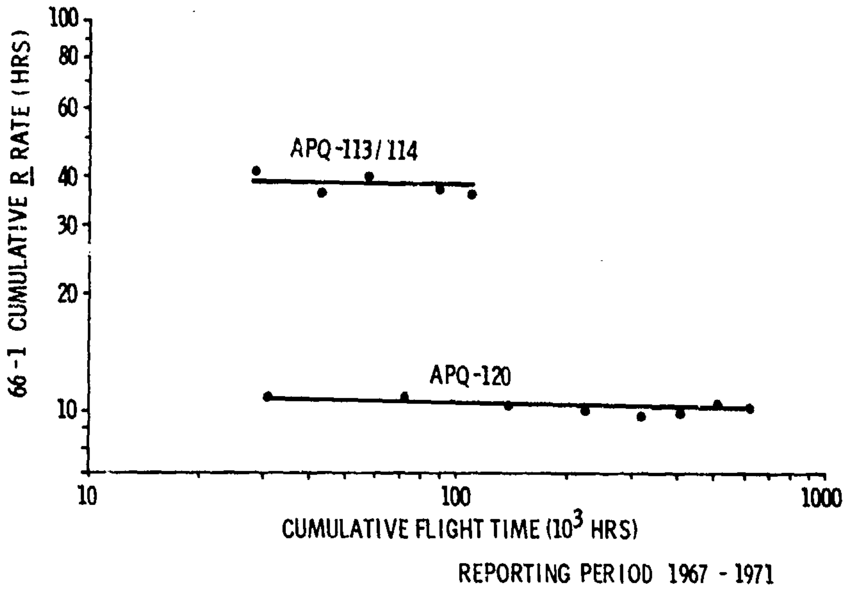

Figure 92. Field Reliability vs Flight Time, APQ-120 vs APQ-113/114

I. RELIABILITY OF ELECTRICAL, ELECTRONIC AND ELECTROMECHANICAL PARTS

1. OBJECTIVE

The primary objective of this subsection is to compare the experienced part failure rates at two levels of radar deployment outside factory (i.e., platform and field) for the two radars. A secondary objective is to identify the contribution of each generic part type to total failures caused by parts. These comparisons will be used to analyze the relative merits of various screening tests employed by the two contractors at piece part level and higher assembly tests.

2. SUMMARY

The observed APQ-120 part failure rates are higher than those of the APQ-113/114 by an order of magnitude (except for inductive and specialty devices). APQ-113/114 platform failure rates are mostly lower than or equal to APQ-120 field failure rates, reflecting the benefits of assembly burn-in and screening for modules, specialty devices and LRU burn-in in weeding out of infant mortality failures.

It would appear from the data available that up to a 50 percent improvement in APQ-120 field reliability could be accomplished by development of corrective actions in two commodities: mechanical parts and diodes. Data analysis points to wear-out or vibration-caused effects for the mechanical parts and inadequate screening or circuit misapplication of diodes. Thirty-two percent improvement in APQ-113/114 field reliability could be accomplished by improved screening or circuit design changes associated with inductive devices and transistors. It also appears from available data that up to a 42

percent improvement in APQ-120 platform reliability could be achieved by improved screening and corrective action for modules and specialty devices.

3. DATA ANALYSIS

Parts performance analysis is based on 66-1 data (RCS 5-Log-K-261). It must be recognized that 66-1 data refer to "Part Replacements" which include both primary and secondary failures and furthermore do not represent all proven defective parts. Platform data was obtained from prime contractor's reports. "Failure" rates were computed using the accumulated platform and field hours and the piece part count of the respective radars, exclusive of parts in potted modules.

Part failure rates for APQ-113/114 radars and the APQ-120 radar are tabulated for several generic part types in Table XXXVII. The failure rates shown are categorized by the two levels of deployment, i.e., platform and field, and a comparative performance between the two radars is computed expressed as a ratio of APQ-120 to APQ-113/114 data.

TABLE XXXVII. DEVICE/PART PERFORMANCE COMPARISON, APQ-120 VS APQ-113/114

GENERIC PARTS	PART FAILURE* RATE $X10^{-6}$ APQ-113/114 PLATFORM	APQ-113/114 FIELD	APQ-120 PLATFORM	APQ-120 FIELD	APQ-120 / APQ-113/114 PLATFORM	APQ-120 / APQ-113/114 FIELD
CAPACITORS	1.64	0.14	9.1	1.25	5.5	9.0
DIODES	3.64	0.82	43.0	12.00	11.8	14.6
INDUCTIVE DEVICES	11.00	5.00	30.8	11.00	2.8	2.2
INTEGRATED CIRCUITS	2.96	0.32	58.3	10.6	19.5	33.0
RESISTORS	0.89	0.20	12.5	2.2	14.0	11.0
SPECIALTY DEVICES	59.00	6.0	128.0	21.0	2.2	3.5
TRANSISTORS	10.3	1.09	114.0	12.5	11.0	11.5
MECHANICAL PARTS			66.6	101.0		
POTTED MODULES			196.0	28.5		

*PLATFORM/FIELD REPLACED PARTS

What emerges from inspection of Table XXXVII are lower failure rates for all parts in the APQ-113/114 radars, especially for semiconductors and resistors. This can be explained by inspection of Table XIII which presents a comparison of parts screening requirements for the two radars. Another observation one can make is that APQ-120 field part failure rates are equal to or worse than APQ-113/114 platform failure rates (except for capacitors and specialty devices). Thus, it appears that platform integration of the APQ-120 accomplishes the same screen as the factory LRU burn-in on APQ-113/114.

Table XXXVIII ranks the parts replacement percentages for the two radars. Several observations can be made by inspection and may be used in future studies to improve field reliability.

TABLE XXXVIII. PART REPLACEMENT RATES RANKING, APQ-120 VS APQ-113/114

APQ-120				APQ-113/114			
FIELD		PLATFORM		FIELD		PLATFORM	
MECHANICAL PARTS	34%	MODULES	27%	MISCELLANEOUS	17%	TRANSISTORS	25%
DIODES	13%	SPECIALTY DEVICES	15%	INDUCTIVE DEVICES	16%	SPECIALTY DEVICES	25%
MODULES	12%	DIODES	14%	TRANSISTORS	16%	MISCELLANEOUS	12%
SPECIALTY DEVICES	12%	TRANSISTORS	14%	SPECIALTY DEVICES	15%	DIODES	10%
MISCELLANEOUS	11%	RESISTORS	12%	DIODES	14%	RESISTORS	7%
RESISTORS	7%	MECHANICAL PARTS	7%	RESISTORS	10%	MAJOR PROCUREMENT ITEMS	6%
TRANSISTORS	6%	MISCELLANEOUS	4%	MAJOR PROCUREMENT ITEMS	6%	INDUCTIVE DEVICES	6%
CAPACITORS	2%	CAPACITORS	4%	INTEGRATED CIRCUITS	4%	INTEGRATED CIRCUITS	5%
INDUCTIVE DEVICES	2%	INDUCTIVE DEVICES	3%	CAPACITORS	2%	CAPACITORS	4%
INTEGRATED CIRCUITS	1%						
TOTAL	100%	TOTAL	100%	TOTAL	100%	TOTAL	100%

APQ-120 data shows that mechanical parts are the main offenders in the field (34% of all field replacements). This contrasts with only 7% contribution for the platform performance. Thus, it appears that a wear-out failure mechanism occurs in the field or that the relative in-flight vibration levels precipitate mechanical failures. Diodes are second on the list in the field and third in platform performance with

comparative percentage distributions of 13% and 14% respectively, leading to a conclusion that a better parts screening or review of electrical stresses/application could provide a payoff.

In the case of the APQ-113/114, inductive devices and transistors share equally the highest percentage contributions (16% each) to field failures by part commodities. Again, a review of parts screening specifications or parts applications is in order. Increased parts screening is suggested by the fact that transistor failures contribute 25% of total failures at platform level and drop down to 16% in the field.

Failure distribution ranking at platform indicates that in the APQ-120 radar the first exposure to a flight environment acts as a severe screen for the encapsulated modules - 27% of all failures. This suggests that an environmental screening of the modules, at lower assembly level, would be beneficial. For the APQ-113/114 platform, it can be generally noted that a uniform distribution of failures occurs.

SECTION VII

CONSIDERATIONS FOR FUTURE PROCUREMENTS

A. INTRODUCTION

This section provides the study contractor's recommendations for changes to specifications and procurement practices for reliability management in development contracts, based on the APQ-113, -114, -144 and APQ-120 Radar Reliability programs and results.

B. SUMMARY

This section contains the following subjects:

- Specific recommendations addressing

  Reliability Contracting Policy

  Reliability Contracting Practice

  Preprocurement Practice

  Procurement Practice

- Recommendations for procurement documentation changes and additions to:

  MIL-STD-781

  MIL-STD-785

  MIL-HDBK-200 (X) (proposed)

- Recommendations for every element of the equipment Life Cycle from concepts, to development, to production, to deployment, and maintenance.

C. CONCLUSIONS/RECOMMENDATIONS

1. RELIABILITY CONTRACTING POLICY

- Insure that MIL-STD-785 is imposed on avionics contracts

- Elevate the stature of reliability requirements in the overall program context so that tradeoffs as a minimum will be on a par with other major performance requirements.

- Instill the fear of failure to meet contractual reliability requirements on both sides -- the contractor and the government program manager.

- Motivate the contractor to identify and resolve equipment problems early in the development phase.

- Use Life Cycle Cost projections when allocating reliability investment and production costs.

- Initiate additional Retrospect Studies to quantize reliability discipline payoffs in Life Cycle Costs.

- Modify present MIL-STD-781 and MIL-STD-785 per suggestions put forth in this section and estabiish a Reliability Training Manual (MIL-HDBK-200(X)) also outlined herein.

2. RELIABILITY CONTRACTING PRACTICES

a. Procurement Requirements

- Realistically establish and dimension the reliability requirements.

- Provide for reliability growth programs.

- Objectively evaluate the contractor's ability to comply.

- Establish reliability technical milestones for development.

- Specific pass/fail progress measurement criteria.

b. Development Contract Penalties

- Test and corrective action continuance until the reliability requirements are achieved.

- Production authorization held until the reliability requirements are achieved.

- Correction of deficiencies in delivered hardware.

- Extended contractor in-service warranties.

- Assumption of upward provisioning requirements resulting from nonconforming reliability.

- Penalties tied to nonachievement of the planned growth rate using the RPM model.

3. PRE-PROCUREMENT

a. Conceptual Phase

Initiate reliability activity in the advanced development phase.

- Estimate equipment and LRU electrical/mechanical piece part complexity.
- Project the expected MTBF performance of the proposed equipment through comparison with field performance of similar systems.
- Analytically project the equipment MTBF capability through existing prediction techniques, e.g., MIL-HDBK-217A.
- Conduct life cycle cost estimates on the predicted range of MTBF values and select optimum point.
- Identify potential state-of-the-art problem areas and initiate programs to alleviate, i.e., low degree of design inheritance.
- Structure program schedules, recognizing the need for reliability growth in development.

b. RFQ Phase

Structure RFQ requirements.

- Based on the MTBF minimum acceptable limit, specify the maximum piece part complexity of the equipment, e.g., the equipment piece part makeup shall be less than 2000 parts.
- Specify MTBF as follows:

  MTBF of 300 hours minimum

  MTBF of 500 hours goal

- Require a reliability prediction estimate of MTBF to be supplied in the proposal that is 125% of the minimum requirement and delineates the equipment parts complexity, material quality levels, failure rates used, environmental K factors applied, and justifications for same.

- Require contractor estimation of MTBF "off the board" as a percentage of prediction and require justification of this estimate based on recent contract performance test data or field performance.

- Require a test plan submission to "grow" the "off the board" MTBF to the minimum acceptable requirement with a minimum/maximum growth rate.

- Require continuing MIL-STD-781 qualification and acceptance testing subsequent to the growth test.

- Require the submission of a product operational environmental burn-in plan (nominally 100 hours) requiring 50 hours of failure-free test on each equipment to the worst case environmental conditions

- Structure correction of deficiency clauses.

- Structure penalty program to lack of MTBF achievement.

- Require reliability program milestone event plan.

c. Source Evaluation

Establish Contractor Proposal Reliability Credibility Review Checklist for source evaluation.

- A comprehensive reliability assessment checklist should be developed to allow an in-depth review of a prospective contractor's intent to comply with the reliability requirement. A properly structured Source Evaluation Checklist would, in addition, encompass the following questions:

  - Does priced bill of material correlate with the quality of material used in prediction?

  - Is there visible evidence of intent to screen 100% of product in the specified environment as evidenced by test facilities quoted, schedule time, etc. ?

  - What is the contractor's track record as it relates to previous performance and timeliness of R achievement?

  - Is Design Inheritance explained and justified? (Design Inheritance: The degree of performance assurance obtained by incorporating proven design features.)

4. PROCUREMENT

Monitor contractor development preproduction performance.

- Measure performance against program reliability

- Monitor design growth through monthly submittals of updated predictions.
- Monitor effectiveness of reliability growth test through monthly submittals of actual test progress versus growth model.
- Monitor reliability test results.
- Approve effectiveness of corrective action steps.

D. PROPOSED SPECIFICATIONS CHANGES

1. MIL-STD-781 PROPOSED REVISIONS

a. Objective

Introduce into test planning the Reliability Planning and Management methodology by recognizing the initial performance immaturity of newly developed equipments. This testing prior to qualification provides:

- Extended orderly environmental test
- Early problem identification
- Incorporation of corrective actions
- Measurement of resultant growth

to insure meeting contractual reliability requirements early in the product cycle.

b. Summary

- Require reference to a new Military "How To" Handbook on Reliability Planning and Management
- Development and inclusion of new Test Plan XXX Reliability Growth Test (RGT)
- RGT required prior to Reliability Qualification and Reliability Acceptance Test
- Provide measurement of reliability growth to a predetermined model
- Require a reliability prediction $\geq$ 1.25 specified MTBF

c. MIL-STD-781 Detailed Revision Changes

The revision changes are presented in specification paragraph number order and associated summary of contents.

2.0 <u>REFERENCED DOCUMENTS</u>

2.1 (Requires reference to a new "How To" MIL Handbook "200 X" describing the implementation alternatives and relative values within reliability program structuring

(Add as last item under 2.1)

PUBLICATIONS

MIL-HDBK-200X Reliability Planning and Management

4.2 TEST PLAN (modify to read)

Test Plans. When reliability assurance tests in accordance with MIL-STD-781 are required, testing will consist of a reliability growth test (see 4.2.10), a reliability qualification (demonstration) test (see 4.2.3), and reliability production acceptance (sampling) tests (see 4.2.4).

4.2.1 Add item

(6) Reliability Growth (Test Plan XXX.)

4.2.1.1 Add

The Reliability Growth Test applies to newly developed or substantially redesigned complex equipment to identify inherent defects in the design, manufacture and quality for the development and validation of corrective action.

4.2.1.2 Start with

The initial preproduction product(s) shall be submitted to the Reliability Growth Test in accordance with the requirements of Test Plan XXX. Upon successful completion of the Reliability Growth Test, the initial production lot of equipment may be submitted to the Qualification (demonstration). Phase test .... etc.....continue with present wording.

Add

4.2.10 Test Plan XXX (Reliability Growth Test).

4.2.10.1 GENERAL

This test plan is intended for use on preproduction equipments, for the purpose of initiating and sustaining reliability growth as a function of the development, incorporation, and validation of corrective actions. This plan is not applicable to Reliability Acceptance Test; however, it can be used in conjunction with the Reliability Qualification Test.

4.2.10.2 TEST PERIOD

The number of equipments and Test duration shall be in accordance with the provisions of Test Plan XXX.

4.2.10.3 EVALUATION OF TEST

To monitor whether R is growing at the projected rate during the Reliability Growth Test, the growth slope shall be equal to or greater than the contract specified, as measured linearly on the log log plot of cumulative MTBF (cumulative failures/cumulative hours) versus cumulative hours. When growth slope is less than the contract specified, the procuring activity shall be immediately notified and mutually acceptable recovery effort and corrective action shall be constituted and implemented. (See Figure 4.2.10.)

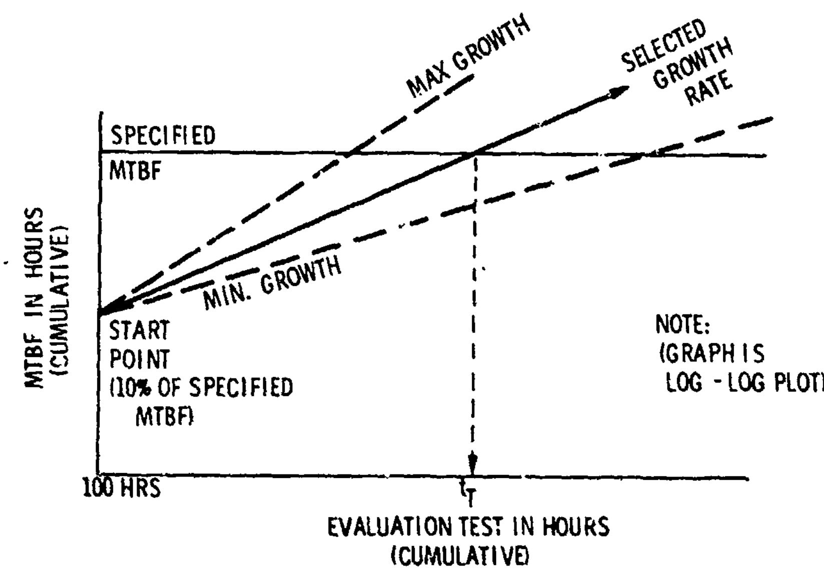

Figure 4.2.10. Reliability Growth Model

RELIABILITY GROWTH TEST MODEL

Instructions for Figure 4.2.10

1. Using log-log graph paper, label axes per Figure 4.2.10.
2. Draw horizontal line at the specified MTBF value.
3. Plot START POINT at 100 hours and 10% of specified MTBF value.
4. From START POINT, draw lines at

   Max. Growth - Slope 0.6
   Min. Growth - Slope 0.1

(NOTE: This slope is measured physically or linearly on the graph, not using logarithmic measurement).

5. Draw line representing Selected Growth Rate with slope between max. and min. lines.

6. Intersection of SPECIFIED MTBF and SEL. GROWTH lines yields T_t, an approximation of the Evaluation Hours Required.

7. Tradeoff Time, Cost, Test Equipment, Prime Equipment, Corrective Action Cycles involved to achieve T_t. Select another value of Growth Rate until satisfied with tradeoff.

8. During actual testing, plot cumulative values of MTBF versus Evaluation Hours. Compare with Selected Growth Rate. Modify actual growth rate by selecting more/less intensive corrective action implementation. Once the actual rate of growth follows the planned rate, the measured equipment MTBF will become the key indicator of when the specified MTBF has actually been achieved. See Section II for definition and determination of "measured MTBF."

5.1.1 (Substitute for the second sentence these two sentences)

FAILURE RATE PREDICTION

At the point of initial design release, the summation of the realistically derived failure rates shall provide an overall failure rate prediction no greater than the reciprocal of 125% of the specified MTBF. Failure to comply shall require a design hold, immediate notification of the procuring activity and a mutually acceptable design iteration plan shall be instituted.

2. MIL-STD-785 PROPOSED REVISIONS

a. Objective

The objective of these revisions is to introduce into program structuring the Reliability Planning and Management methodology to recognize reliability growth in complex equipments. This Study demonstrates initial reliability performance of complex product to be typically 10% of that which is realistically predicted. This methodology provides the management tools to:

- Dimension the effort
- Allocate resources
- Assess risks
- Schedule work tasks

to insure meeting contractual reliability requirements early in the product cycle.

b. Summary

- Require development of Reliability Growth Test Planning Model
- Require R prediction $\geq$ 1.25 specified MTBF
- Recognize initial product capability at 10% of inherent predicted capability.
- Establish R program planning options versus constraints
- Provide early and continuous Reliability program progress and visibility
- Establish auditable Reliability program planning as a key element in source evaluation review

c. MIL-STD-785 Detailed Revision Changes

The revision changes are presented in specification paragraph number order and associated summary of contents.

FOREWORD (Revise entirely to read)

The reliability achieved by military systems is directly dependent upon the reliability requirement imposed and upon the emphasis placed on reliability by (Government and Contractor) management throughout the development life cycle. In order to achieve specified reliability and to do it early in the life cycle, it is necessary to dimension (through a reliability growth model) the extent of evaluation and corrective actions reasonably required as a part of the design and development phase. The basis for the structuring of Reliability Growth Test Planning Model is in accordance with MIL-STD-781 Test Plan XXX and MIL Handbook "200 X", auditable by and subject to the approval of the procuring activity as a part of the final source selection decision for development contract award. It is intended that the mandatory criteria provided herein aid in the timely and economical attainment of reliability requirements as an integral part of the general process by which acceptable levels of system performance and life cycle cost are achieved.

2. REFERENCED DOCUMENTS

2.1 (Requires reference to the to-be-developed Military "How To" Handbook on Reliability Planning and Management.)

MIL-HDBK-200X - Reliability Planning and Management

4. GENERAL REQUIREMENTS

4.1 (revised to read)

The contractor shall establish and maintain an effective reliability program that is planned, integrated, and developed in accordance with Military Hand-

book "200 X" Reliability Planning and Management, in conjunction with the other design, development, and production functions, to assure the timely and cost effective achievement of the contract specified reliability requirement, optimization of equipment development, and total life cycle costs. The program shall assure reliability involvement throughout all aspects of the design, development, and production with firm management commitment to meet the contractual reliability requirements.

5. DETAILED REQUIREMENTS

5.1.2.1 Add Item

(1) A Reliability Growth Test Planning Model in accordance with MIL Handbook "200 X" Reliability Planning and Management Section 5.1.

NOTE: Renumber items (1) - (8) as (2) - (9).

5.1.4 Program Review (modify to read)

The Reliability program shall be planned and scheduled to permit the contractor and procuring activity to review its status including results achieved, at preplanned steps or milestones. The following mandatory reporting requirements are established.

a) Review of failure rate prediction 30 days prior to design release to establish that realistic and suitable failure rates have been utilized and that the summation of the failure rates, i.e., scope of the physical implementation, supports a prediction at a minimum 125% of the specified MTBF.

b) Review of the finalized Reliability Growth Test Planning Model and all associated planning and procedures including, but not limited to, test equipment schedules, number of equipments under test, spares support for the equipment under test, test procedures, stress levels, growth rates, and corrective measures.

c) RGT progress shall be reported every 30 days through the submittal of an up-to-date Growth Model chart showing the MTBF achieved as compared to Projected Growth. Corrective action status shall be highlighted for all failures. Only externally induced failures shall be classified as non-relevant. The procuring activity shall be notified at least 10 days prior to each contractually scheduled formal reliability program review to permit possible participation by the procuring activity. The minutes of these formal reliability program reviews shall be made available to the procuring activity upon request.

5.2.2.3 Reliability Apportionment/Prediction (add)

d) The reliability prediction based on the technically established and credible failure rates above, will yield, at a minimum, a prediction that is 125% of the specified MTBF requirement.

5.3.2 Development Testing (Replace completely)

A Reliability Growth Test shall be structured and conducted in accordance with MIL-STD-781 Test Plan XXX for all pre-production contracts. The Growth Model is predicated on the following criteria:

a) Initial Performance - A realistic appraisal be made of the new or changed equipment design, recognizing the presence of flaws which constrain initial performance to 10% of the inherent predicted capability.

b) Reliability Growth - The rate of reliability improvement (for complex equipment) is approximately inversely proportional to the square root of the cumulative operating (test) time. For a constant level of corrective action effort and timely implementation, reliability growth closely approximates a straight line on a log-log plot.

c) Limits of Reliability Rate of Growth - Limits are estimated as a maximum of approximately 0.6, a rate of 0.5, for an aggressive reliability program. A minimum rate of 0.1 can be expected on those programs where no specific consideration is given to or for reliability.

d) Product Evaluation Exposure - The test evaluation time required to effect a compliant product is based on (a) Prediction at 125% of required MTBF, (b) Initial performance, (c) Reliability Growth Rate. With the exposure hours thus established, and a valid assumption on achievable test efficiency, then the tradeoffs in program planning can be objectively made by contractor and buyer, encompassing (a) the acceptability of the initial design, (b) its design margin, (c) number of equipments to be placed on test, (d) facilities, (e) test time, (f) calendar time, and (g) ultimately, program cost.

Successful completion of the test shall be the achievement of the specified MTBF in accordance with the approved Reliability Growth Test Planning Model. Reliability Demonstration Test shall be conducted only after successful completion of the Reliability Growth Test.

3. PROPOSED HANDBOOK FOR RELIABILITY PLANNING AND MANAGEMENT

a. Objective

One recommendation of this study is that DOD provide for a handbook of the proposed reliability management concepts for application in government and industry. Such a handbook could be incorporated into existing documentation; however, it is recommended that a separate handbook be considered. As the methodologies described in this study are further developed and, as new methodologies are discovered, these would be added to such a manual.

The following outline provides the foundation for such a program manual to be developed.

> As we make an all-out effort to improve our capability for the utilization of advanced management techniques such as RPM, it is of vital importance that this capability be communicated to Planning Functions as well as Implementing Functions. This can be accomplished by carefully laid plans to identify, orient, train, and certify such users. Some of the typical groups in both Government and Industry that must be indoctrinated are:
>
> Project Managers
> Estimators
> Contracting Officers
> Engineering Administrators
> Design Engineers
> Reliability and Quality Engineers
>
> Government and Industry should jointly identify a total training program in this area to be implemented as rapidly as planning guidelines can be developed.

4. OUTLINE FOR PROPOSED MIL-HANDBOOK (200X) - RELIABILITY PLANNING AND MANAGEMENT

SCOPE

Provide a manual of reliability Program Management tradeoffs and methodologies, suitable for application by DOD and industry management, quantifying the relative values of reliability activities for optimization of individual equipment developments and their total life cycle cost.

CONTENTS

System

- Life cycle cost modeling and experience model verifications
- Budget percentage of R&D contract value to allocate for R
- Factory reliability to field reliability correlations and λ factors
- Factory-to-field failures, similar/dissimilar
- Quantize reliability effects on operational readiness and mission abort rate

Product

- Provide reliability disciplines versus cost/time tradeoffs

- Dimension reliability design disciplines (e.g., value of parts screening, standardization and derating)
- Assign reliability value to computer-aided design
- Structure Reliability Planning and Management (RPM)
- Detailed procedures for measuring reliability growth
- Determine reliability effects on true Product Manufacturing cost
- Quantize reliability (MTBF) effect on logistics support cost

Reliability Program Tools and Techniques

To be selectively utilized during Design, Design Evaluation, and Development to provide the Reliability Growth needed to meet Requirements.

- Parts Standardization - the most piece parts using the fewest number of drawings, i.e., the least number of different parts for the functions required. A suggested ratio overall is 20:1.
- Material Quality - the quality of parts used and the extent to which such quality can be improved by Parts Screening, Burn-In, Supplier Control and Surveillance.
- Assembly Quality - the quality of such assemblies assured by establishing equipment and personnel standards, operator training, station controls, and corrective action data systems.
- Data System - to provide basic data for a given program and to enable comparison of like programs using basic parameters such as Cumulative Test Hours and Cumulative MTBF to facilitate retrospect studies and correlation.
- Failure Incidence (by part type) - per 1000 processed during manufacture and assembly to allow economic application of corrective action.

To be utilized in Evaluating Prediction of Reliability

- Design Inheritance - direct benefits from proven designs
- Screened Parts (versus Unscreened Parts) - effect on Failure Rates used.
- Failure Rates - compare with published rates using RADC, HDBK 217A.
- Screened Parts - check effect on parts prices
- Parts Standardization - minimum number of drawings used, i.e., minimized number of different parts.

- Major Procurement Items - reliability prediction, use of screening and suppliers controls

PROPOSED MIL HANDBOOK (200 X)

- Quality Plan - effective product flow, inspection and testing plan, manufacturing and process controls. Responsive to change based upon quality data.

- Manufacturing Plan - Product flow, assembly and processes detailed in planning. Planning documented and controlled.

APPENDIX

SPECIAL TERMS AND ABBREVIATIONS

Alpha (α) Growth Rate	A term used to dimension the reliability growth rate - see Analytical Section (α derivation)
ASM	(See Assembly)
Assembly	A number of parts or subassemblies or any combination thereof joined together to perform a specified function
BI (Burn-In)	Product Environmental Screening
CID	Change-in-drawing notice, the GE/AESD document which authorizes and describes Engineering changes to released drawings and parts lists
ETI (ETM)	Elapsed Time Indicator
Field	Encompasses the final as deployed status (AF) within which the treated radars were studied
IC	Integrated circuit
ID	Inductive devices
IPC	The GE inspection planning that defines test inspection characteristics and quality levels to appraise specific operations, products and supplier material
LCC	Life Cycle Cost as used in this study - based solely on cost of maintenance attributable to equipment reliability performance
LRU	Line Replaceable Unit APQ-120 } See Equipment APQ-113/114/144 } Description section

M Rate	"Mean time between maintenance" as reported in the 6 Log K 261 (66-1) USAF report
MISC.	Miscellaneous parts (sockets, fuses, terminals, plugs, switches, lamps, meters, etc.)
MMH/FH	Maintenance Man-Hours/Flight Hours
MPI	Major Procurement Items (7 items in APQ-113/114/144 including ARCA, TRCA, D/A Converter, Servo Amplifier A&B, Camera and HVPS)
MTBF	Mean Time Between Failure
MTBA	Mean Time Between Aborts
MTBMA	Mean Time Between Maintenance Actions
Part	Items such as resistors, transistors, capacitors, diodes, integrated circuits
Platform	The radar installation and acceptance cycle at the prime airframe contractors (McDonnell Douglas and General Dynamics)
PPL	Preferred Parts List
Pre-Release	The portion of contract phase including the design, development and qualification (design and reliability) tests
R Rate	"Mean Time Between Failure" as reported in the 6 Log K 261 (66-1) USAF report
RAT	Reliability Acceptance Test
RDT&E	Research, Development, Test and Evaluation
RET	Reliability Evaluation Test
RPM	Reliability Planning and Management
RQT	Reliability Qualification Test (synonymous with demonstration)

S/A	Subassembly, two or more parts which form a portion of an assembly or an item replaceable as a whole, but having a part or parts which are individually replaceable
Screened Parts	Environmentally screened and burned-in parts, performed at the part level by part vendors or by manufacturers prior to assembly
Serviceable	Items which tested OK in Air Force maintenance shops after being removed from aircraft, normally reinstalled without repair
Specialty Device	Specialty Devices (Gyros, Motors, Filters, Relays, LVPS, Tubes, etc.)
Systematic Failures	Pattern failures not part of the original prediction, which can be detected, corrected and eliminated via a test program
TAAF	Test, Analyze and Fix, also RET testing
Unit (Equipment)	A major assembly consisting of any combination of parts, subassemblies, and assemblies packaged together as a physically independent entity

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13. ABSTRACT

The purpose of this study was to provide insight into Reliability Worth through quantifying the relative values of reliability activities and their impact on life cycle costs. This study is based on APQ-120 and APQ-113/114/144 Radar reliability data, spanning only a specific time period of their development, and therefore the findings presented are limited to the equipment configurations included in the data base and the specific time period studied. In-service reported reliability performance data was analyzed for both radar families, the objective being to correlate differences in reliability performance with the equipment reliability requirements and programs structured. Reliability program elements instrumental to the development effort are analyzed to determine relative worth. Considerable emphasis is placed on reliability evaluation testing, parts screening, and equipment burn-in which are identified as major contributors toward achieving demanding equipment reliability performance. This report finds that optimum maturity of radars, prior to deployment, requires extensive and well-directed development effort as an investment measured in cost and time. The report also recognizes and supports the importance of uncompromising contractual incorporation of MIL-STD-781 at applicable airborne stress levels as the principal driving force in establishing and executing effective reliability development effort. Based on the experience of the equipments studied, it is concluded that timely, sufficient and properly directed reliability program investment can produce significant cost savings leverage when compared against the projected equipment life cycle maintenance costs for unreliable equipment. Recommendations are provided, based on conclusions derived from study findings, relative to reliability contracting practices, prerelease disciplines and testing programs, specifically applicable to high performance aircraft avionics equipments.

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14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Radar - APQ-113						
APQ-114						
APQ-120						
APQ-144						
Reliability Testing						
Reliability Growth						
Reliability Performance						
Reliability Cost and Value						
MIL-STD-781						
MIL-STD-785						

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